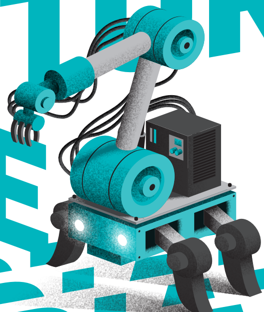
ARCHITECTURE IN THE AGE OF THE 4TH INDUSTRIAL REVOLUTION



Edited by
José Pedro Sousa
Gonçalo Castro Henriques
João Pedro Xavier

Volume I
The eCAADe and SIGraDi Conference
11-13 sep 2019, Faculty of Architecture
University of Porto, Portugal

eCAADe SIGraDi 2019

Architecture in the Age of the 4th Industrial Revolution

Volume 1

Editors
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eCAADe SIGraDi 2019

Architecture in the Age of the 4th Industrial Revolution

Volume 1

Proceedings

The 37th Conference on Education and Research in Computer Aided Architectural Design in Europe

The 23rd Conference of the Iberoamerican Society Digital Graphics

Conference

11th-13th September 2019
Porto, Portugal
Faculty of Architecture
University of Porto

Edited by
José Pedro Sousa
Gonçalo Castro Henriques
João Pedro Xavier

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PREFACE

This is the first volume, of three, of the Proceedings of the 37th eCAADe and the 23rd SIGraDi Conferences, held as a Joint Event from 11-13 September 2019 at the Faculty of Architecture of the University of Porto, in Portugal. The three volumes together contain the 221 accepted papers that are also available digitally at CumInCAD (Cumulative Index of Computer Aided Architectural Design) – http://papers.cumincad.org

Theme

"We stand on the brick of a technological revolution that will fundamentally alter the way we live, work, and relate to one another. In its scale, scope and complexity, the transformation will be unlikely anything humankind has experienced before."
Klaus Schwab, *World Economic Forum*, 2015

Looking for confronting the discipline of Architecture with the most critical topics nowadays, the eCAADe SIGraDi Conference 2019 was dedicated to the theme of:

Architecture in the Age of the 4th Industrial Revolution

Going back in history, the 1st Industrial Revolution occurred between the 18th and 19th centuries, when water and steam power led to the mechanization period. By then, social changes radically transformed cities and, together with manufactured materials like steel and glass, promoted the emergence of new building design typologies like the railway station. In the end of the 19th century, the advent of electrical power triggered mass production systems. This 2nd Revolution affected the building construction industry in many ways, inspiring the birth to the modern movement. For some, standardization emerged as an enemy of arts and crafts, while, for others, it was an opportunity to embrace new design agendas, where construction economy and quality could be controlled in novel ways. More recently, electronics and information technology fostered the 3rd Revolution with the production automation. In architecture, the progressive use of digital design, analysis and fabrication processes started to replace the traditional means of analogical representation. This opened the door for the exploration of a higher degree of design freedom, complexity and customization. The rise of the Internet also changed the way architects communicated and promoted the emergence of global architectural practices in the planet.

Today, in the beginning of the 21th century, we are in a moment of profound and accelerated changes in the way we perceive and interact with(in) the world, which many authors, like Klaus Schwab, do not hesitate to call as the Fourth Industrial Revolution. Extraordinary advancements in areas like mobile communication, artificial intelligence, big data, cloud computing, blockchain, nanotechnology, biotechnology, facial recognition, robotics or additive manufacturing are fusing the physical, biological and digital systems of production. Such technological context has triggered a series of disruptive concepts and innovations, like the smart-phone, social networks, online gaming, internet of things, smart materials, interactive environments, personal fabrication, 3D printing, virtual and augmented realities, drones, self-driving cars or the smart cities, which, all together, are drawing a radically new world.

Challenges

Like in the past, if the world changes, the discipline of architecture cannot remain indifferent. It must understand and adapt to the new circumstances and why not, orient some of the undergoing transformations. Since digital technologies are at the core of the emerging paradigm, the eCAADe SIGraDi Conference 2019 became a privileged space to promote a comprehensive discussion about the place and role of Architecture in the Age of the 4th Industrial Revolution. Therefore, we invited researchers, professors, professionals and students to address questions like:

- *What is the impact of new technologies in architectural education and practice?*
- *What are the emerging opportunities and threats to our discipline caused by the rise of new intelligent processes and material systems?*
- *How are architects balancing between resistance and adoption regarding the convergence of cyber, physical and biological systems?*
- *How can digital technologies contribute for a better and more responsible built environment?*

The topics proposed for the Conference included, but were not limited to:

AI for design and built environment
Additive manufacturing and construction
Art and Design
Big data and analytics in architecture
Building Information Modelling
City Information Modelling and GIS
CAAD Education and teaching
Collaborative and participative design
Cyber-physical systems in architecture
Design concepts and strategies
Design thinking and methods
Digital design for sustainable buildings
Digital fabrication and robotics
Digital technologies for cultural heritage
Digital research in architectural practice
Generative design
Game design technology
History and Future of CAAD
Human-computer interaction
Internet of things in architecture
Interactive and responsive environments
Material studies and innovation
Parametric and algorithmic design
Simulation, prediction and evaluation
Smart Cities
Virtual and Augmented Reality

The first volume of the proceedings contains 89 papers grouped under 12 topics, the second volume contains 95 papers grouped under 12 topics, and finally the third volume contains 37 papers grouped under 4 topics. In addition to the accepted papers, we acknowledge our guest speakers in the first volume and the workshops organized the days before the Conference in the third Volume.

José Pedro Sousa, Gonçalo Castro Henriques and João Pedro Xavier
eCAADe SIGraDi 2019 Conference Chairs

FOREWORD - eCAADe

Dear eCAADe and SIGraDi friends,

The Porto eCAADe/SIGraDi conference invites ‘academicians, researchers, professionals and students to address how digital technologies are shaping the place and role of architecture in the age of the 4th industrial revolution.’ I believe the question of how architecture can lead the process of shaping its own and other digital ecologies is of equal importance in a world irrevocably interconnected by digital infrastructures.

I consider this joint conference a unique opportunity to celebrate the idea of togetherness and collaboration I promoted during the last two-years, and as such I’m happy my eCAADe presidency ends here, in Porto. I promoted togetherness and collaboration not only with eCAADe’s sister organisations (SIGraDi, ACADIA, CAADRIA…) but also with EAAE (European Association of Architectural Education) and ARENA (Architectural Research European Network Association). Interconnectedness in architectural education and research is becoming a tradition: with the biannual conferences of EAAE and ACSA (Association of Collegiate Schools of Architecture) or EAAE and ARCC (Architectural Research Centers Consortium). The Porto conference as a unique—joint—experience of two regionally rooted associations is powerful evidence of this flow, as well as of the new role of eCAADe and SIGraDi turning into intensively connected global players in architectural as well as design computing.

I believe that both eCAADe and SIGraDi can benefit from a deeper understanding of the different educational and research contexts needed for the quality of and the engagement in the umbrella activities of all sister organisations, such as the CUMINCAD database and the IJAC journal.

The eCAADe association—Education and research in Computer Aided Architectural Design in Europe—has advanced considerably from its original CAD-related investigations. It is mature enough to take new directions. I believe after this immersive event we are ready to develop a new vision that will define our own identity. When I discussed this with Joachim Kieferle, our

Vice President Emeritus and Birgul Çolakoğlu, our Vice President Elect, a temporary new name for eCAADe emerged: Education in Computing for Advanced Architectural Design in Europe. I believe that the Porto conference can contribute in shifting our emphasis from aspects of architectural computing to the essence of the convergent thinking and future oriented design processes enabling us to overcome problems such as open-ended processes, resilience and risk.

‘Art and Design’ as one of the joint conference topics is new on the eCAADe list, and now, after more than ten eCAADe conference years, I am happy that architecture is the first word of this conference title. Some of the questions now confronting us are: What are the contemporary and future architectural practices; how can we achieve design leadership in architectural computing for sustainable environmental solutions; how can we evidence our (academic) research impact of that leadership without counting citations; and what are the skills needed for designing the architectural designer’s careers in the 4th industrial revolution?

I’m looking forward to discussing these and other relevant questions in Porto. I would like to thank all the people who made the eCAADe/Sigradi event possible. Especially to you, José Pedro Sousa and Gonçalo Castro Henriques, for your initiative and excellent organizational efforts. To the people from the initial joint Working Group: Henri Achten, Birgul Çolakoğlu, Gonçalo, Rodrigo Martin İglésias, Pablo Herrera and Marcelo Bernal. I’m very grateful to you two, Joachim Kieferle and Rudi Stouffs, for your additional support during the most intensive preparatory period. Thank you, João Pedro Xavier, we feel welcome to Porto!

Tadeja Zupančič,
President of eCAADe

FOREWORD - SIGraDi

Dear SIGraDi and eCAADe colleagues,

Every year we make a great effort to bring together the members of our Ibero-American Society of Digital Graphics and every time it is a different team in Iberoamérica that takes the enormous commitment to organize our annual conference. Likewise, every year a growing number of members is joining the call to expand and renew our community, building a space to share experiences and ideas. The challenge of organizing the XXIII Congress was taken up by the Faculdade de Arquitectura de la Universidade do Porto, in Portugal, with its chairs, Gonçalo Castro Henriques, José Pedro Sousa, and João Pedro Xavier.

This year is without a doubt special for us, as for the first time in history we are holding a joint Congress of two sister societies in the CAAD field. This event marks a milestone in the development of our paths and opens the door to new ways of exchange and thinking. The idea of holding a joint congress between SIGraDi and eCAADe arises from the topographical. coincidence that occurs in Portugal, which in addition to obviously belonging to Europe, is also part of Iberoamérica, a category embracing all Spanish and Portuguese speaking countries in America plus the Iberian Peninsula (Portugal and Spain). This coincidence, however, was only a starting point, since it required a great deal of work on the part of the organizing committee and the teams designated by both steering committees. Today we can say that it was truly worth it and we can be proud of this historic achievement.

This year the conference motivates us to think and explore about "Architecture in the Age of the 4th Industrial Revolution", being a very suitable topic for our time. We are currently suffering rapid and fundamental transformations in the ways we manufacture, design and project, communicate with machines and cyber-physical systems, or with each other. This situation must be understood as a challenge to our collective future, a challenge of planetary scale. The era of the Anthropocene demands urgent solutions to problems created by ourselves. It is an urgent need to modify our practices, ways of living and ways of producing. This is everyone's responsibility, but fundamentally that of the decision-makers.

Finally, it is very important to highlight the relevance of this gathering of continents and cultures in the current context, where the latent threat of xenophobia, discrimination, and nationalist fundamentalism becomes increasingly visible. Our meeting is therefore also a signal for the future that challenges the geopolitical order, as a message of intercultural coexistence, a plea for respect of differences, and for open and distributed knowledge.

Our both societies are sustained by a legacy of decades of effort, but above all, it is sustained by people and collectives embodying our common quests and interests. We are part of something bigger than ourselves, something that surpasses and expands us, but that depends on each and every member of the community. Years ago, we began a path full of curiosity, which makes us wait every year for this very moment of meeting and collective reflection, of reunion and celebration. Now we face challenges that we want to face together.

Rodrigo Martin-Iglesias,
President of SIGraDi

ON THE eCAADe SIGraDi JOINT CONFERENCE 2019

The 2019 Conference in Porto joins, for the first time, two major Associations in the field of Digital Technologies in Architecture – eCAADe (Europe) and SIGraDi (Iberoamérica) - to debate together about **Architecture in the Age of the 4th Industrial Revolution**.

Background

The beginning of this journey started in 2015. Following the organization of the 1st eCAADe Regional International Workshop (RIW) "Future Traditions" at FAUP in 2013, José Pinto Duarte challenged José Pedro Sousa to submit a proposal to host the Annual eCAADe Conference in Porto. Despite the enormous difficulty and responsibility of undertaken such task, that possibility looked very opportune for the Faculty of Architecture of the University of Porto (FAUP) and for the City of Porto. Widely recognized for its pedagogy and the architecture of Álvaro Siza and Souto de Moura, the event could strengthen the relevance of technology in the School and stimulate its singular potential to bridge traditions with digital innovation. On the other hand, aside with its rich heritage legacy, the city of Porto has become a vibrant place for the arts, architecture, culture and entrepreneurship, and such fact sets the perfect atmosphere for hosting the event.

Thus, in 2016, a submission to debate the place of Architecture in the Age of the 4th Industrial Revolution was submitted to the eCAADe Council and, during the 34th eCAADe Conference in Oulu, the Faculty of Architecture of the University of Porto (FAUP) was then elected to organize the 37th eCAADe Conference in 2019 in the city of Porto, following the editions in Rome (2017) and Lodz (2018).

Later, in the other side of the Atlantic Ocean, during the XXI SIGraDi Conference in Concepcion (Chile 2017), Gonçalo Castro Henriques made a proposal to SIGraDi Council CEI that was accepted, to invite the FAUP to also organize the 2019 Conference in the city of Porto. That idea came into life because Portugal, as well as Spain, is officially part of the Iberoamerican

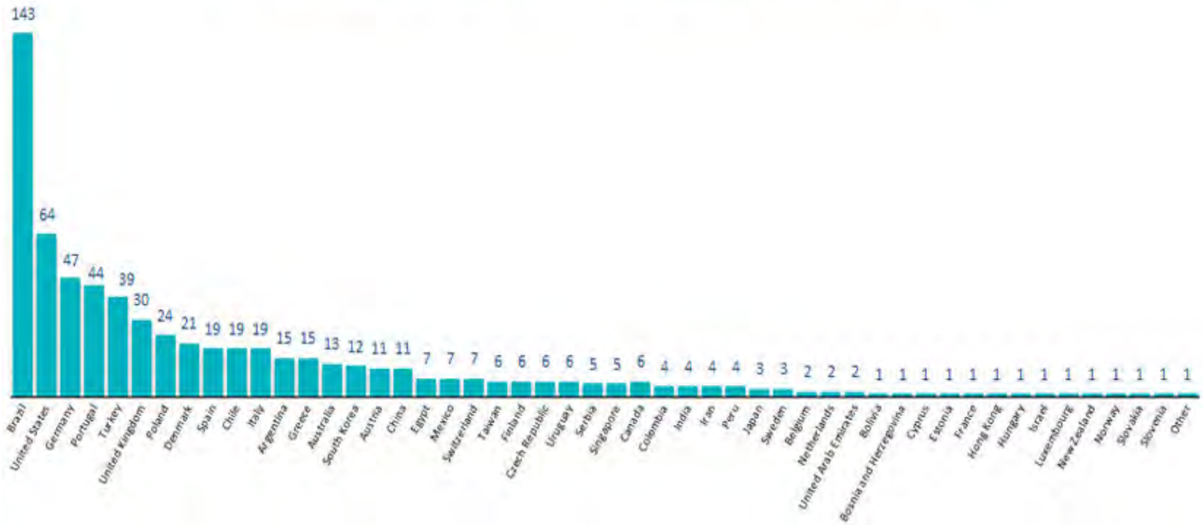
Community. Following the editions in São Carlos SP (Brazil 2018), and Concepcion (Chile 2017), this was a unique opportunity to bring SIGraDi for the first time to the Iberian Peninsula.

Realizing the overlap of the two Conferences in the city of Porto, the possibility to create a Joint event in Portugal emerged as an exciting opportunity for bringing together the two communities and debate a global theme. Such one-time collaborative initiative between eCAADe and SIGraDi would celebrate the openness and exchange of knowledge between countries across continents in a current moment where frontiers and walls seem to be gaining a renewed impetus.

However, moving forward with such challenge required a series of conversations between eCAADe and SIGraDi Councils to find a common ground regarding both associations' traditions and culture. Over several months, formal and implementations issues were discussed to overcome the differences and make possible the ambitious joint initiative. This was facilitated by the fact that the Chairs from both Associations were from the city of Porto, and have collaborated since long ago. After reaching a formal agreement, the Councils of eCAADe and SIGraDi appointed a joint Commission to assist the organization of the Conference. Birgul Colakoglu, Joachim Kieferle, Henri Achten, Rudi Stouffs (eCAADe) and Fernando Garcia Amen, Marcelo Bernal, Pablo Herrera and Rodrigo Martín Iglésias (SIGraDi) were unbeatable with their support and guidance over the months of preparations.

Developments

The unique features of the joint event triggered an immense curiosity and interest in the event. As a result, the Call for Papers received **649** extended abstracts submitted from **50** countries. Such number set a new record in the history of both associations and became a serious challenge for the organization.



Call for Papers results – submissions / country

The review of the extended abstracts (length of 1000 to 1500 words plus 5-10 references and one image) followed the high-quality control process well established in these Conferences. Each submission had to be strictly anonymous and to avoid any affiliations and was evaluated by three reviewers coming from institutions other than the authors. Thanks to eCAADe, we were able to use the *OpenConf System* to carefully manage the entire anonymous submission and evaluation process.

Reviewing such large number of abstracts was only possible with the professionalism and generosity of our Scientific Committee composed by **203** reviewers from **40** countries. To accomplish the 1947 required reviews, we created a special group of experienced reviewers - *the Expert Group / Champion reviewers* - who accepted to evaluate a greater number of submissions than usual, and to whom we are especially thankful. We pay tribute to each of the reviewers in the reviewers list.

The review process was concluded with the selection of **269** abstracts from **39** countries for further development as a Full Paper. The submission process of the Full Papers was then handled through the *Proceedings Platform* and resulted in the final publication of 221 works.

In parallel to the Conference preparations, we organized a Call for Workshops that received 21 proposals. Out of these, 6 workshops were selected and added to the 3 Workshops proposed by our main sponsors *Autodesk*, *Graphisoft* and *Dassault Systèmes*. Following the tradition of eCAADe and SIGraDi Conferences, and the spirit of the current edition, a Joint PhD Workshop was organized by Wolfgang Dokonal (eCAADe) and Gabriela Celani (SIGraDi). The PhD Workshop Committee selected a total of 10 PhD students to come to Porto and discuss their research with an experienced team of international critics. The 9 Workshops and the PhD Workshop were featured as Pre-Conference events happening from 9-10 September.

Conference

The eCAADe SIGraDi Joint Conference attracted 300 participants to the Faculty of Architecture of the University of Porto (FAUP) from 11-13 September. For organizing the sessions, we defined 6 main themes to frame the different specific session topics. Following this organization, 221 presentations unfolded through 4 parallel sessions over the three conference days.

Design	Algorithmic and Parametric Artificial Intelligence Collaboration and Participation Generative Systems Shape Grammars and Ruled Based Systems
Matter	Additive Manufacturing Digital Production and Robotics Fabrication and Construction Material Studies and Innovation
Data	Building Information Modelling City Information Modelling and GIS Cultural Heritage Smart Cities
Interaction	Human-Computer Interaction Responsive environments
Simulation	Prediction and Evaluation Virtual and Augmented Reality
Challenges	Art and Digital Poesies Big Data and Analytics Education and Research History and Future CAAD Sustainability +Cultural Heritage

Theme structure ruling the Conference Session topics

Such structure is also reflected in the organization of the current publication, where each volume is matching each Conference day.

The four Keynotes were invited to provide particular, but complementary, visions addressing the spirit and theme of the event. Thus, we were grateful to count with:

- Professor Mario Carpo (UCL), discussing the theory and critic of the digital revolution;
- BIG (Bjarke Ingles Group) Associate and BCN Design Director João Albuquerque, featuring the work of one of the most distinguished international practices today;
- Professor Gabriela Celani (UNICAMP) tracing the panorama of the 4th Industrial revolution in the Iberoamérica;
- Architect Marta Campos (Porto-based office), revealing the fusion between tradition and digital innovation on a young, small and local practice.

In order to establish a special moment for collective discussion, Professor José Pinto Duarte (PSU) was invited to Chair of a Roundtable about the Architecture in the Age of the 4th Industrial Revolution. To host all these special moments with a wider audience, we resort the Theatre Campo Alegre, nearby FAUP.

Aside with the Conference sessions, a series of special social programs were also organized for each night, flowing from the City Hall of Porto, the Fenianos Club, the Douro River, the Alfândega Building, the Nuno Centeno Art Gallery, and the City Downtown.

We this intensive and vast program, we tried to stimulate the scientific exchange between peers from each Association, but also the establishment of friendship links between them. Although from next year on each association will return to their independent annual Conferences, we hope this joint initiative can trigger new productive collaborations between the two communities and thus extend the spirit of the eCAADe SIGraDi 2019 over time.

José Pedro Sousa, Gonçalo Castro Henriques and João Pedro Xavier
eCAADe SIGraDi 2019 Conference Chairs

ACKNOWLEDGEMENTS

Our first thanks go to all Paper Authors featured in the current Proceedings, Session and Roundtable Chairs, Keynotes, the technical Workshop tutors and the Joint PhD Workshop organizers, whose role was determinant for the success of this ambitious initiative. Thanks also to the international Scientific Committee – both Champion and Regular Reviewers – who evaluated the 649 extended abstracts. Such demanding task was only accomplished thanks to eCAADe for providing access to the OpenConf System, to Martin Winchester and Pablo Herrera for helping us operating with it, to Gabriel Wurzer, Wolfgang Lorenz and Ugo Maria Coraglia from the ProceeDings team for enabling the successful production of this extensive publication, and to Bob Martens for the CumInCAD integration.

This one-time Joint Conference would not have been possible without the commitment of the eCAADe and SIGraDi Presidents, Tadeja Zupancic and Rodrigo Martin Iglésias, and the Council Members. We thankful them for embracing the challenge of this collaborative initiative and trusting our team to make it reality. It's never enough to remind the decisive support we got from the Joint Committee members - Birgul Colakoglu, Joachim Kieferle, Henri Achten, Rudi Stouffs (eCAADe) and Fernando Garcia Amen, Marcelo Bernal, Pablo Herrera and Rodrigo Martín Iglésias (SIGraDi) – and also from past eCAADe Chair Anetta Kepczynska-Walczak and past SIGraDi Chair David Sperling who kindly shared with us their experience and recommendations.

At FAUP, we are thankful to former and current Directors, Carlos Guimarães and João Pedro Xavier, who supported hosting the event at the School since the beginning. We also want to express our gratitude for their invaluable help and generous time to our local team and the staff at FAUP, in particular, to Pedro Varela, Pedro Martins, Cláudia Almeida, Fábio Saraiva and Carolina Medeiros. We are also in debt to Tânia Santos (Modal Creativity), studio DOBRA (designers), Maria João Sá and Susana Bettencourt (CM Porto), Gonçalo Castro (ATP&N) and Cristina Oliveira (TMP Campo Alegre) for their dedicated and productive collaboration.

A final word to acknowledge our *Diamond sponsors* Autodesk, Graphisoft and Dassault Systèmes, *Gold Sponsor* Bentley Systems, *supporters* Santander Universidades, Fundação para a Ciência e Tecnologia, Amorim Isolamentos, Finsa, OEI, as well as our *Institutional Partners* Teatro Municipal do Porto - Campo Alegre and the City Hall of Porto.

José Pedro Sousa, Gonçalo Castro Henriques and João Pedro Xavier
eCAADe SIGraDi 2019 Conference Chair

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Gabriela Celani

Keynote : ***Shortcut to the 4th Industrial Revolution: The Case of Latin America***

Gabriela holds a BA and an MSc in Architecture and Urban Design from the University of São Paulo, and a PhD in Design and Computation from the Massachusetts Institute of Technology (MIT). She is presently a Professor of Architecture and Urban Design at the University of Campinas (Brazil) and has been a visiting scholar at Universidad Nacional del Litoral (Argentina), Universidade Técnica de Lisboa and MIT. In 2006, she founded LAPAC, the Laboratory of Automation and Prototyping for Architecture and Construction. Her work focuses on generative design, rapid prototyping, digital fabrication and automation of the architectural design process. She was vice-president of institutional relations of the SIGraDi from 2013 to 2015, and belongs to the scientific committees of several CAAD conferences, such as ECAADE, CAADRIA and DCC, acting also as a reviewer for journals such as Design Studies, IJAC, AIEDAM and Automation in Construction. Gabriela Celani was the chair of CAAD Futures Conference 2015, held in Sao Paulo, and is the treasurer of the CAAD Futures Foundation since 2017. In the same year, she received from SIGraDi the Arturo Montagú Prize for her academic trajectory.

Marta Campos

Keynote : ***Digital Building Revamp***

Marta Campos is head of “Marta Campos – Architecture”, Porto based BIM addicted architectural atelier, passionately engaged in delivering architectural services, ranging from renovation to new construction. Due to market request most of her work as been on building renovation, leading to the foundation of “Norte Magnético” a company specialized in Entrepreneurship Management of building rehabilitation.

João Albuquerque / BIG

*Keynote : **Past to Future***

João Albuquerque, BIG Associate and BIG BCN Design Director, is going to discuss BIG's philosophy, evolution and adaptation during a decade of work, and present projects that explore how architecture can challenge the future of our world. BIG (Bjarke Ingels Group) is a Copenhagen, New York, London and Barcelona based group of architects, designers, urbanists, landscape professionals, interior and product designers, researchers and inventors. The office is currently involved in a large number of projects throughout Europe, North America, Asia and the Middle East. BIG's architecture emerges out of a careful analysis of how contemporary life constantly evolves and changes. Not least due to the influence from multicultural exchange, global economical flows and communication technologies that all together require new ways of architectural and urban organization. In this context, Past to Future presents the work by BIG from Yes is More to Form-giving, from Denmark to Mars.

Mario Carpo

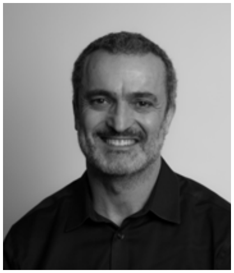
*Keynote : **Computational Brutalism***

Mario Carpo, Reyner Banham Professor of Architectural Theory and History, the Bartlett, University College London. Carpo's research and publications focus on the relationship among architectural theory, cultural history, and the history of media and information technology. His Architecture in the Age of Printing (2001) has been translated into several languages. His most recent books are The Second Digital Turn: Design Beyond Intelligence (2017), The Alphabet and the Algorithm, a history of digital design theory (2011); and The Digital Turn in Architecture, 1992-2012, an AD Reader.

ROUNDTABLE CHAIR

José Pinto Duarte

Roundtable topic : ***Architecture in the Age of the 4th Industrial Revolution***



José P. Duarte is a Professor of Architecture and Landscape Architecture at the Penn State Stuckeman School of Architecture and Landscape Architecture, where he holds the Chair in Design Innovation and directs the Stuckeman Center for Design Computing. Duarte holds a professional degree in architecture from the Technical University of Lisbon and master's and a PhD in Design and Computation from MIT. He was Dean of the Faculty of Architecture, University of Lisbon, and president of eCAADe, a European association devoted to education and research in computer-aided design. His research focuses on the use of computation and AI to support context-sensitive design across different scales. Recently his team was awarded the 2nd place in finals of NASA 3D-Printed Mars Habitat Challenge aimed at the construction of a subscale habitat.

Design - GENERATIVE SYSTEMS

Aesthetic Quantification as Search Criteria in Architectural Design

Archinder

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The paper describes a research experiment of incorporating quantitative aesthetic evaluation and feeding the metric back into a parametric model to steer the search within the design space for a high-ranking design solution. The experiment is part of a longer-standing interest and research in quantitative aesthetics. A web platform inspired by dating apps was developed to retrieve an aesthetic score of images (drawings and photographs of architectural projects). The app and scoring system was tested for functionality against an existing dataset of aesthetic measure (triangles, polygon nets). In the actual experiment, an evolutionary algorithm generated images of design candidates (phenotypes) and used the aesthetic score retrieved by the ``crowd'' of app users as a fitness function for the next generation/population. The research is in the tradition of empirical aesthetics of G. T. Fechner (Fechner, 1876), using a web app to crowdsource aesthetic scores and using these to evolve design candidates. The paper describes how the system is set up and presents its results in four distinct exercises.

Keywords: *Quantitative Aesthetics, Social Media, Crowdsourcing, Collaborative Design, Human-Computer interaction*

INTRODUCTION - AESTHETIC QUANTIFICATION

The research is presented in two parts: Firstly, it proposes a method for establishing a quantitative aesthetic measure. Secondly, it sets out the experiment where that measure is used to navigate the solution space of a parametric model.

At first, an aesthetic score for a set of images has to be established. This is done by recording the hedonic response individuals show towards a set of images. The mechanism is to present the images and record the responses to that in a social media app. A hedonic response is a judgement of liking or disliking something (Shimamura, 2014). One good example of an application of digitally enabled hedonic judgement is online dating apps like Tinder, where on one side you make an aesthetic judgement of liking or disliking photographs of other people, and by the other side, you share pictures of yourself to (hopefully) be liked by others. A system like that allows to translate a qualitative appreciation of images into a quantitative count of likes or dislikes: an aesthetic score.

When establishing an aesthetic measure, the research builds on the field of empirical aesthetics, which was established by the German philosopher, physicist and experimental psychologist Gustav Theodor Fechner (1801-1887). Fechner proposed a scientific method to evaluate human sensation that co-relates physical stimuli to it (Fechner, 1876). In this way, he avoided dealing with complicated philosophical questions and focused on how simple elements, like geometrical shapes and colours, produced effects on humans and how much they are liked in comparison with each other in a quantitative fashion.

There is a broad body of work on the question of why we appreciate some objects more than others with conclusions from different perspectives and from different disciplines, like psychology, neurology, philosophy, art history... However, the present work will focus on hedonic responses and not in the deeper aesthetic reasons.

The second part of the work is an experiment questioning how that measure could be fed back into a design process. We defend that besides structural, environmental and economic criteria, architecture could benefit also from an aesthetic evaluation when looking for design solutions. Antecedents application of a qualitative aesthetic-based search in the solution space are Sjoberg et. al that uses supervised Machine Learning to navigate the solution space (Sjoberg et. al, 2017) and Yusif et. al that incorporates form diversity and user interaction as parameters in Multi-Objective Genetic Algorithms (Yusif et. al, 2017). Other precedents are the research done at the "Brain Hacking" studio by Toru Hasegawa, Mark Collins and Anna Stork at Columbia GSAPP with eye-tracking and EEG and a business application of quantitative aesthetics analysis is incorporated by Google to design its results pages (Granka et al. 2008).

One of the contributions of our proposed method is to implement social media web interfaces for crowdsourcing aesthetic evaluation. As a test group, 10 undergraduate architecture students coming from different countries used our mechanism. During one month, they fed our system with their hedonic evaluation and, in the end, used it for a design proposal.

METHODS - SYSTEM SETUP AND TESTS

Our system is separated in 3 elements:

1) Form Generating Parametric Model (FGPM)
2) Evolutionary Algorithm (EA)
3) Web Platform (WP)

The first element, FMPM, is open to any designer able to work with Rhinoceros and Grasshopper. It's a parametric model able to produce different designs according to a combination of parameters, therefore producing a design solution space. In the present paper, two different FMPM were developed by us and will be presented in the next chapters: (A) Single triangles and (B) Polygon nets. Also, the participants of this experiment developed their own FMPM for architectural elements, as presented in chapter D of this paper.

For the second part, an Evolutionary Algorithm (EA) was used to search the design space of the FMPM. Our EA inserts random values into the FMPM to create the first generation of design solutions and capture an image for each one. After receiving an aesthetic score of each solution from the Web Platform (WP), our EA creates new solutions tending towards the most liked previous images to create the next generations of drawings. The algorithm was run daily to upload newer images to the WP until it stabilizes, which means when the solutions are all too similar.

The last element of the system is the Web Platform (WP) with Graphic User Interface, a responsive web application with a custom server running on a cloud instance. It receives all images from all design solutions and presents it to the participants with a Graphic User Interface that mimics Tinder (Figure 1): It shows the image with a like or dislike button below and, also, allows the participant to swipe it left (dislike) or right (like). Every day the WP sends the aesthetic score to the EA, ranging from 0 (most disliked) to 1 (most liked).

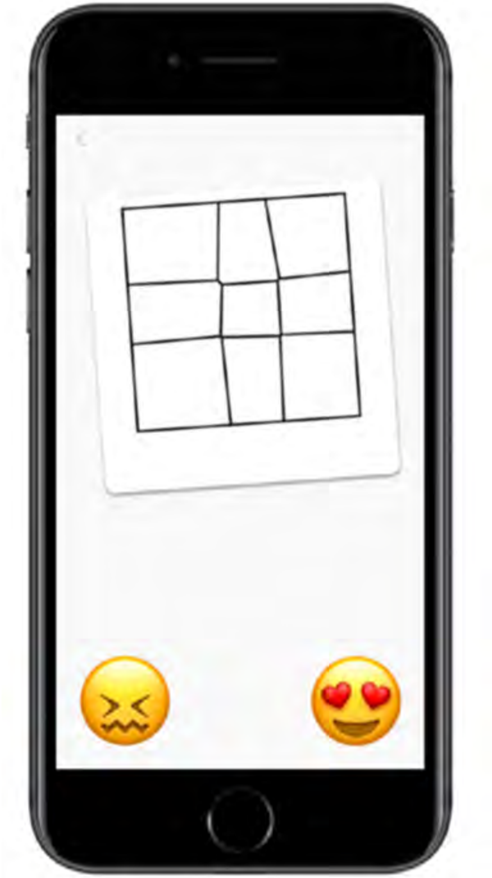


Figure 1
Graphic User Interface of Archinder running on a smartphone.

RESULTS AND DISCUSSION

The paper will present four outcomes from Archinder that deals with specific problems:

- A - Triangle Proportions (to test the overall functionality of the system),
- B - Polygon net (to evaluate complexity),
- C - Historical images (to add more image related evaluation) and
- D - Architectural Elements (to allow participants to introduce their own designs).

A - Triangle Proportions

To determine if the whole system is working accordingly and to refer to existing research on perception, we realized a test based on established conclusions on the appreciation of symmetric triangles. Using hedonic responses, the state of the art research asserts that equilateral triangles receive more positive reactions than triangles with other proportions (Friedenberg, 2012). As Jay Friedenberg argues, "triangles that are more compact are less likely to move or break and are thus considered more pleasing".

From the first generation of randomly generated triangles, the system rapidly converged and produced equilateral triangles in the second generation. In the coming generations, the solutions became stable, not varying largely. It proved that the system was behaving as expected.

B - Polygon Net. Between Boring and Disturbing: The problem of Complexity

The second test focused on comparing the hedonic response of perceived simplicity and complexity. As a form making mechanism, the Voronoi diagram was adopted considering that it can produce complex geometry, simple grids and all sorts of variation between both.

The first generation, that was randomly produced, exhibited simple grids and highly intricated polygons. The next two generations, fed by the data from our system, created solutions in between both extremes until it reached stability from the 4th generation onwards. This is a good example of the application of our system because Polygon Net operates with a very high number of variables.

In these images, complexity could be measured according to the variation of the size of cells and differences in the shape of each polygon. These results suggest that humans favour mild complexity.

Daniel Berlyne defends that humans are not at-

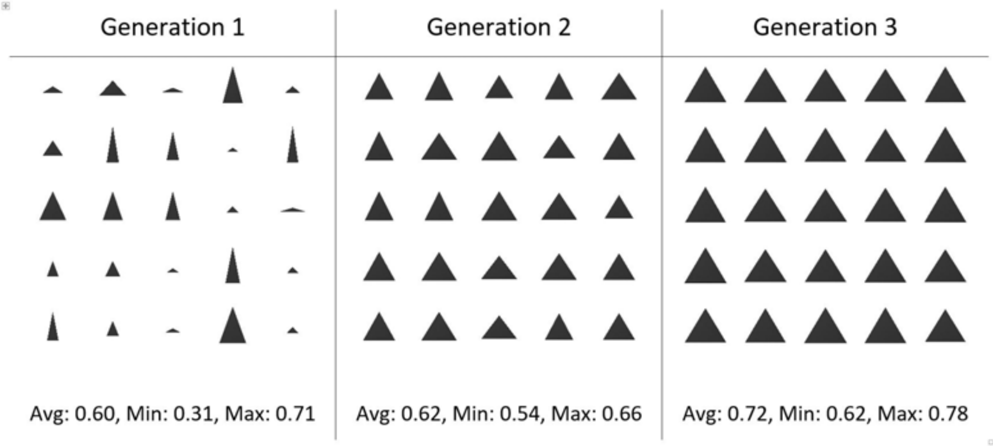


Table 1
Three generations of triangles created by our Genetic Algorithm. Avg: Average Score, Min: Minimum Score, Max: Maximum Score

tracted by images that do little to arouse curiosity nor by works that are overpowering and causes confusion and displeasure (Berlyne, 1971). Berlyne argues that we prefer some novelty, surprise, complexity and incongruity but in excess, it causes a negative experience. Here it's important to note that this aesthetic theory is based on what we, as subjects, were previously exposed, defending that it's not an inborn mathematical proportion issue.

C - The Problem of Images

We decided in the next experiment to feed our system with existing pictures to avoid geometry and incorporate other qualities like colour, texture and shadows. Each student was asked to select their ten favourite buildings and upload one picture of each. In this case, we could only assert an aesthetic score to each according to the number of likes and dislikes, ranging from 0 (most disliked) to 1 (most liked). In this example the FMPM and the EA were by-passed.

It's not the ambition of this paper to make an aesthetic judgement of existing architectural projects, but it's important to note that a few images of the same building received very diverse aesthetical scores. Guggenheim in Bilbao appears twice and its lowest score is 0.380 and highest is 0.629. The Pyramid of Khafre scored 0.476 and 0.714.

D - Aesthetic optimization applied in an Architectural Element

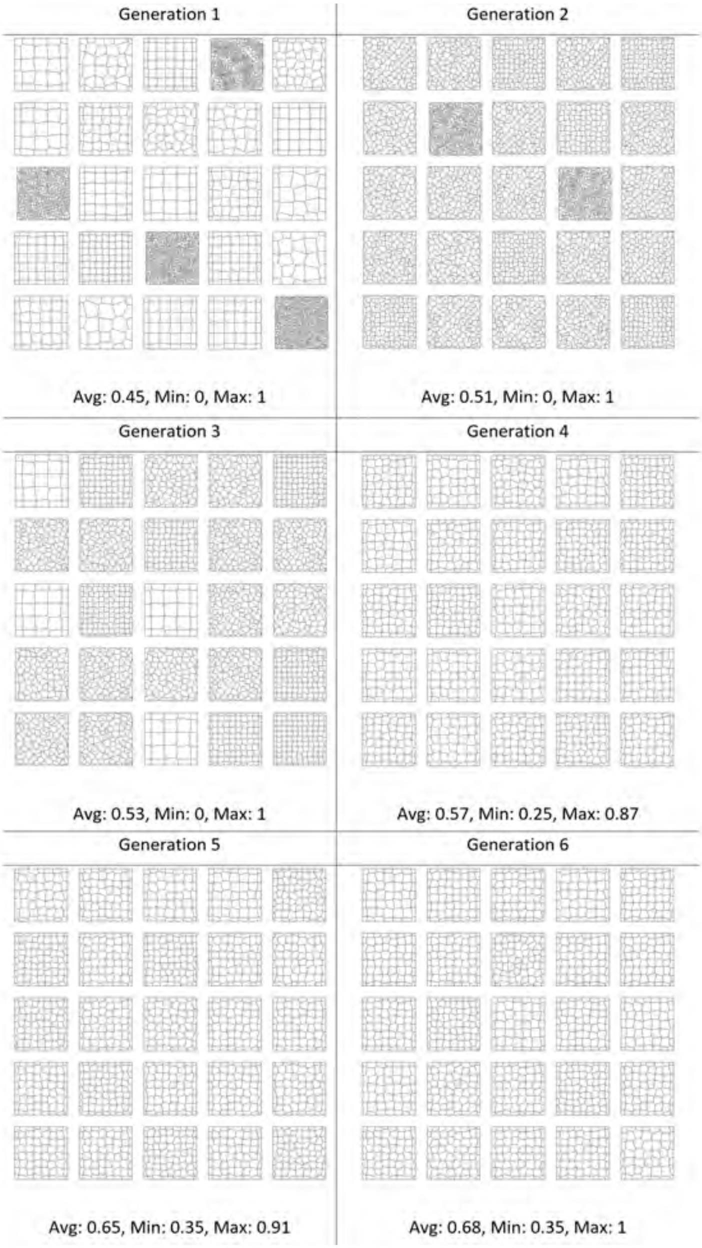
To explore the application of the system, the participants developed their own FMPM of a vertical Architectural Element (Figure 2). All models were incorporated in the EA and uploaded to the WP.

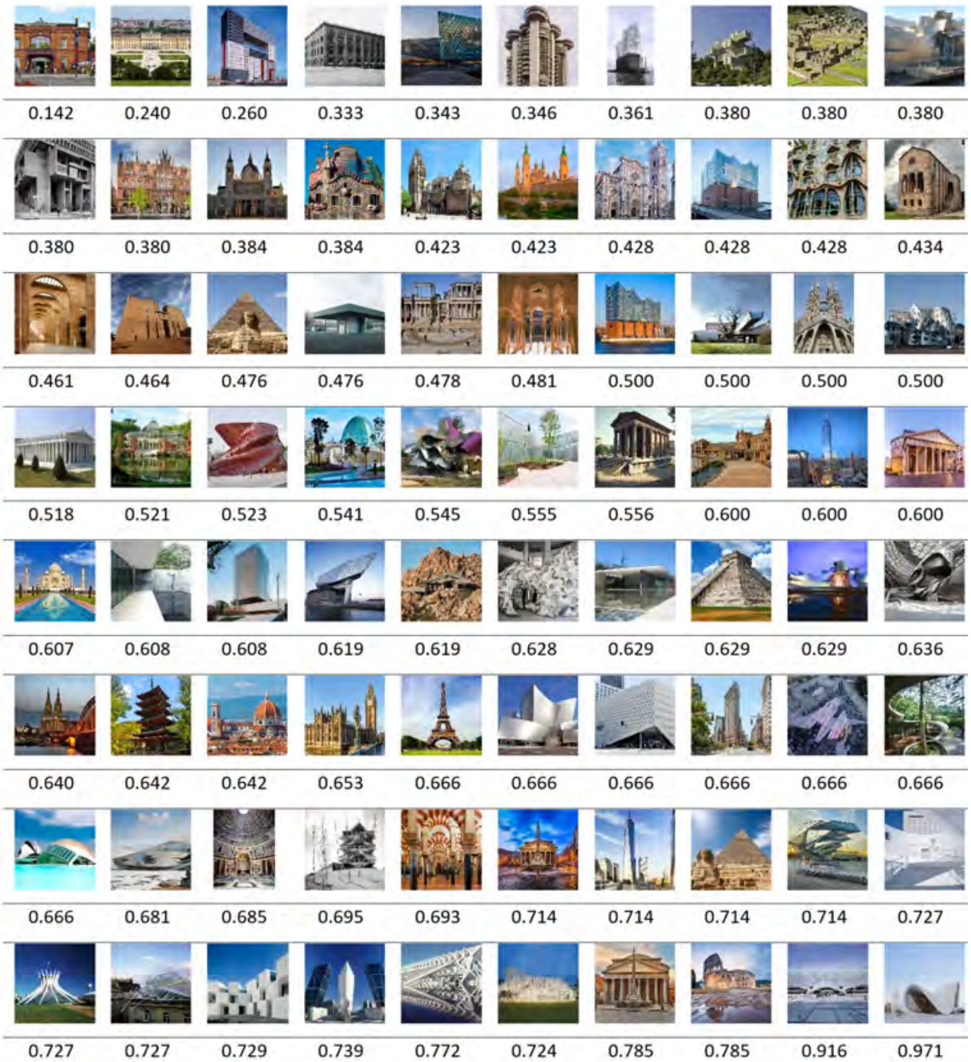
Figure 2
Five vertical architectural elements produced by five FMPM.

In this stage, the system is varying the parameters of each solution within each FMPM and also evaluating between all FMPM. After six generations, the solution with the highest aesthetic score was selected for further development.

This experiment proves that the system works to select architectural forms according to an aesthetic score but it demands more time to stabilize and, therefore, the designers should be aware to restrict the space of solutions. Evolutionary al-

Table 2
Six generations of polygon nets created by our Genetic Algorithm.





0.142	0.240	0.260	0.333	0.343	0.346	0.361	0.380	0.380	0.380
0.380	0.380	0.384	0.384	0.423	0.423	0.428	0.428	0.428	0.434
0.461	0.464	0.476	0.476	0.478	0.481	0.500	0.500	0.500	0.500
0.518	0.521	0.523	0.541	0.545	0.555	0.556	0.600	0.600	0.600
0.607	0.608	0.608	0.619	0.619	0.628	0.629	0.629	0.629	0.636
0.640	0.642	0.642	0.653	0.666	0.666	0.666	0.666	0.666	0.666
0.666	0.681	0.685	0.695	0.693	0.714	0.714	0.714	0.714	0.727
0.727	0.727	0.729	0.739	0.772	0.724	0.785	0.785	0.916	0.971

Table 3
80 photographs
and its respective
aesthetic score

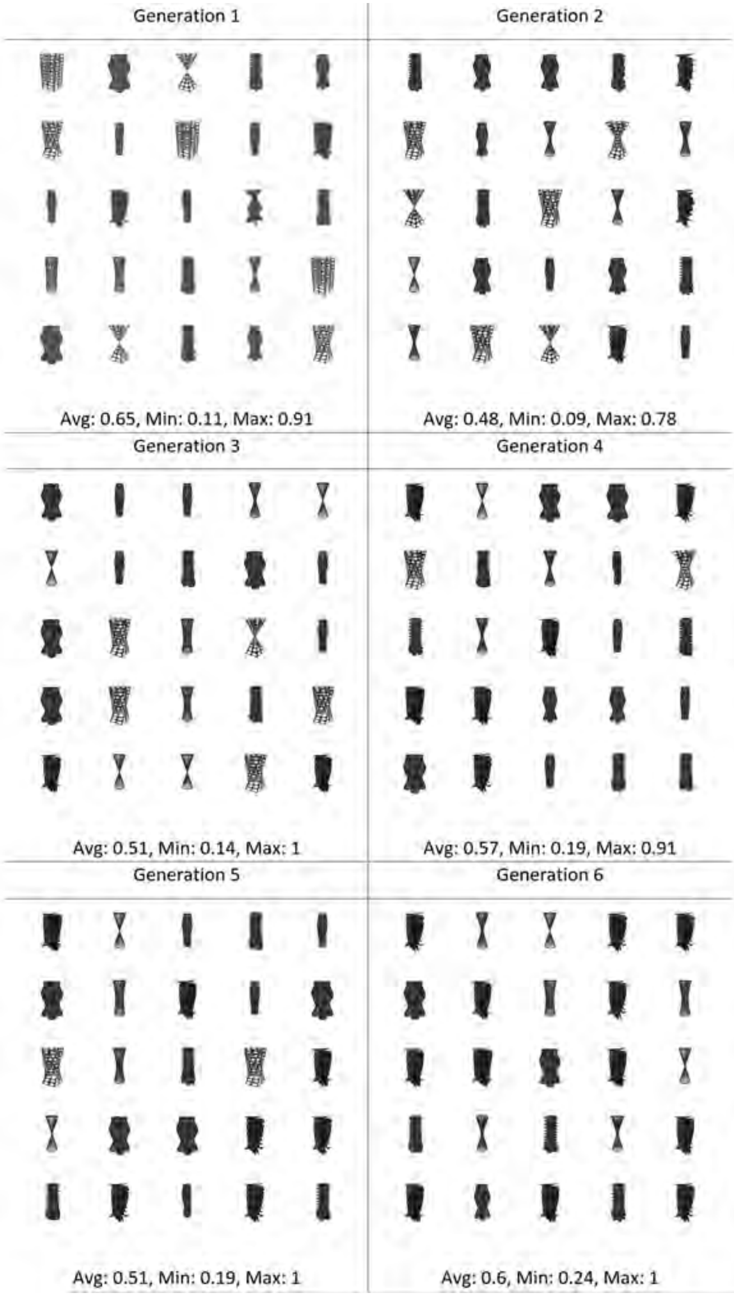


Table 4
Six generations of Architectural Elements created by our Genetic Algorithm.

gorithms in design are very time effective because usually the fitness criteria are calculated by the computer (like structural behaviour, environmental performance, cost estimation...), differing from our human-machine interface, that requires the test group to evaluate each solution.

CONCLUSIONS

The system proved to be a viable way to generate and select design solutions. In our time of big data and fast and cheap computers, it has become possible to generate and test an ever-increasing number of design solutions (Carpo, 2017). However, the criteria for the selection is usually a quantitative analysis that is closer to issues of engineering and economics than to architectural formal problems. Our system introduces the problem of aesthetics as possible criteria for design solution search.

The discrepancies in scores of two photographs of the same building in experiment C with historical images made us realize that the object of analysis in our software is the aesthetic qualities of images themselves, being it drawings, renders of photographs and not necessarily the formal or spatial qualities of architectural projects. Therefore, the way that every image is generated is of primary importance and to compare design solutions it's essential to maintain visual consistency. Future work can go towards purely image evaluation not relying so much upon geometry.

One future development is to incorporate in the system the educational background of each user in order to compare how it influences the aesthetic judgement of images. It was already proven that the brain activity of educated architects and the general public are activated in different manners [7]. So, it will be interesting to see how architects' hedonic responses differ or not from the general public.

Another future development is to make it into a Grasshopper plug-in and make it available for the designer community to test the concept of aesthetic search in different environments, both in the academy and in practice and train Neural Networks according to the community´s hedonic response.

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Generative Systems:

Intertwining Physical, Digital and Biological Processes, a case study

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The fourth Industrial Revolution is characterised by the computational fusion of physical, digital and biological systems. Increasing information in terms of size, speed and scope exponentially. This fusion requires improved, if not new, tools and methods to deal with complexity and information processing. By opening Generative Systems to interact with the context, we believe that they can develop solutions that are more adequate for our time. This research began with a literature review about generative systems and their application to solve problems. We then selected the tools, Cellular Automata, L-Systems, Genetic Algorithms and Shape Grammar, and thought about how to translate these original mathematical tools to specific design situations. We tested the application of these tools and methods in a workshop, implementing recursive loops to open these techniques to interference. Analysing the empirical results made us revise our design thinking, relying on the study of complexity to understand how these techniques can be more context-aware, so we can make design evolve. Finally, we present a comparative framework analyses that interlaces techniques and methods, so in the future we can merge physical, digital and biological information.

Keywords: *generative systems, design thinking, complexity, context interaction, recursion*

RESEARCH APPROACH

To promote Generative Systems in architectural design, we developed a 5-stage process. First, we researched about generative systems and how to apply them. Secondly, we thought about the translation of abstract mathematical techniques to design context. Thirdly, we tested these techniques empirically to gain a better understanding of their capabilities and limitations in a workshop. Fourth, we analysed the tools and methods used and the results for each technique. Results recommended deepening our knowledge about design cognition and complex systems theory. Finally, we synthesised and compared the techniques and design methods.

GENERATIVE SYSTEMS AND COMPLEXITY

The use of generative systems in design, unlike traditional methodology, implies an indirect relation with the final product. Production, rather than being done directly with the "designer's own hands," is mediated by a "generative system" (Fisher and Herr, 2000). To define a generative system, it is necessary to define the abstract set of rules and proceedings that will create a set of objects. If we want this object to make any sense in a certain environment, these rules must be about the object-environment relation. Otherwise, the meaning of the object in a specific context will be a matter of chance.

Generative systems, exploring computational power, can provide unimaginable solutions, expanding creativity. According to Gero (1996), the most common concept of creativity does not consider the ability to develop possibilities during the generation of solutions; only the ability to improve end-product quality. To create multiple solutions, it is necessary to work with methods that explore and record the possibilities of solving a problem, aggregating unexpected and less familiar results usually discarded. Taylor (1972) categorises five types of creativity: expressive, productive, inventive, innovative and emerging. In this context, it is important to emphasise beyond the "emergent creativity", the "productive creativity", that is, the creativity contextualised in the domain of a technique, which allows controlling the project in the environment generated. Architects rely on Design Thinking (Simon, 1969) to help solve ill-defined problems, using mainly implicit design processes instead of linear thinking and with strict criteria. They value the hands-on experience with the tools and their application to find solutions, evaluate and develop them, seldom making any explicit algorithms. We often leave optimisation till the final stages, after defining the form, to improve its performance. However, mathematical optimisation and processes, such as generative systems, have a precise definition and strict procedures to solve problems. So, to understand generative systems, architects must enter the algorithmic process. This requires opening the algorithm "black box", making the mechanisms to produce results explicit, unlike the traditional "hands-on processes", where the final results are felt more directly. In a sense, architects need to cope with extensive processes to expand their abilities.

Composition and Complex Systems

By their education, architects are able to deal with complex problems related with the nature of their work. Beyond "Complexity and Contradiction" (Venturi, 1966), the study of complexity in science has developed to consider complex systems, supported by the evolution of mathematics and computation, a conceptual and technological evolution, intensified now with the fourth industrial revolution disruptive logic (Schwab, 2017).

Complexity is not new in the Design Thinking process. Formerly, architecture was an art in the integrative sense, but, after the Renaissance, it separated into different branches of knowledge in a continuous specialisation process. In architecture, the segregation was not only among disciplines, but between composition and materialisation. Like the architect, the sculptor, the painter, the musician, the chemist and the physicist, all compose (Figure 1). What is the relationship between composition and complexity?

The relationship is closer than one might think. The architect, like other composers, invents the problem - there is no scientific law to describe the context of how an object emerges (Buchanan, 2000 and Stolterman, 2008). Then he formulates circumstantial laws to adapt a methodology that deals with problems beyond linear logic, dealing with implicit subjective techniques, where he intervenes directly. The artist, like the observer in second-order cybernetics, interferes and changes his environment (Dubberly, Pangaro, 2015). When we speak of composition, we use notions such as rhythm, weight, dynamics and static equilibrium, entailing a transition from a part to a whole relationship and vice versa. Therefore, in addition to quantities, the artistic process uses qualities that have implicit measure subjected to an individ-

Figure 1
Composition in different activities: composition as material search in sculpture (Chillida), expressive search in painting (Tapiés 1990), search in mathematics (Fuller 1948), and research in the study of the three-dimensional composition of the double helix (Watson and Crick 1954). Photos in the public domain.

ual learning process. Colquhoun (1989) refers about composition:

"Composition came to mean a creative procedure in which the artist created 'out of nothing' and arranged his material according to laws generated within the work itself ... Form was no longer thought of as a means of expressing a certain idea, but as indissoluble from, and coextensive with, the idea. Composition therefore was able to stand for an aesthetic of immanence in which art became an independent kind of knowledge of the world."

This article does not intend to argue about the dichotomy between art and science, but rather refer to a time when these two areas of knowledge were bound, forming a wholeness. This return to an integrated conception of different branches of knowledge was a necessity in the 50s, a reaction to scientific reductionism, as formulated in the "General Systems Theory". Thus, Integrating knowledge and tools in architecture, promised so much by the introduction of the digital in Architecture, is still to be fulfilled.

Observing the introduction of digital into design, the separation of materialisation and composition or the tool and process dichotomy, seems to persist (Terzidis, 2003). To bridge tooling and the processual use of digital, computerisation and computation, Terzidis proposed Algorithmic Design. The architect's process seems somehow incomplete when he intends to move into the unknown realm of mathematical tools, new "black boxes" he wants to open to incorporate technology and more information. For this, architects rely on exploratory search, a knowledge that has similarities with composition search using analogue or pre-digital generative systems. In this aspect, architects have the ability to invent new realities in other domains (Carpo, 2011). It is precisely because the architect can invent the new that he can contribute to refounding "the science of the artificial" (Simon, 1969). Simon refers to design as indispensable: "The proper study of mankind is the science of design, not only as the professional component of a technical education, but as a core discipline for every liberally educated man."

So, it is not a question of how to apply design to solve complex problems (Herr, 2002). Rather, it is a question of how Design Thinking can (re)invent approaches to Complex Systems. For this, we might remember the characteristics and nature of design problems (Buchanan, 2000). Also, how does artistic composition deal with these new tools? To compose is to establish an order among the parts - even if we do it according to top-down processes (architecture treatises) or bottom-up (rules of composition) - representing an understanding of how things come to be, that is, describing thing also as a process, or method, of design, unifying a set of elements based on the senses and previous experiences. Parallel to art, when science passed from deterministic logic to multi-causal and probabilistic reasoning, it required new tools. In both cases, one can say experimentation is a heuristic process to narrow the computational search space.

Complexity addresses relations among the parts and multiple levels of organisation as well as the relations (and behaviour) of these systems and their environment. Due to its comprehensiveness, Design Thinking can be useful in different areas: a) Visual and symbolic communication; b) Material objects such as products, tools, instruments and machines; c) Organisation of activities and services; d) Complex systems or environments for living, working, playing and learning. (Buchannan, 2000). Applying a synthetic approach to design thinking, in concatenating parts, the whole context is essential for complex systems.

Melanie Mitchell (2009) points out that to understand complex systems, it is necessary to address information, computation, dynamics and chaos, and evolution. In her book, she introduces these subjects in each one of the chapters to set a conceptual framework to define and measure complexity. She measures complexity as: Size, Algorithmic Information Content, Logical Depth, Thermodynamic Depth, Computational Capacity, Statistical Complexity, Fractal Dimension and Degree of Hierarchy. Finally, she concludes, "The diversity of measures that have been proposed indicates that the notions of complexity that we're trying to get at have many different interacting dimensions and probably can't be captured by a single measurement scale."

Complex Systems and Problem Types

According to Weaver (1948), science began by solving simple linear problems with few variables, during the XVII, XVIII and XIX centuries. Then it solved problems of disorganised complexity, with many variables, using statistics. Thus, it solved problems from the atoms to the stars resorting to computation using probability and statistical data. The next kinds of problems to grasp are those of organised complexity, of the mesoscale of everyday life, with more variables.

TRANSLATING GENERATIVE TECHNIQUES

We researched generative systems literature describing the application of these techniques to solve problems, identifying four significant techniques:

Cellular Automata (Neumann, 1951; Wolfram 2002), L-Systems (Lindenmayer, 1968), Genetic Algorithms (Holland, 1975) and Shape Grammar (Stiny, 1980). Each tutor studied one of these techniques along with a group of students, looking for examples and understanding of the type of problems each technique can solve.

We studied the technique's application in practical cases, resorting to the algorithms and descriptions available. For 3 months, a group of researchers identified types of problems, variables and applications, considering the potential and limitations of each technique. This helped to formulate the workshop design problem. References differed in each technique, but we focused on how to implement them in visual programming, testing available applications. Relying on this experience, we prepared a problem and tested it in the Workshop Form Finding and Generative Systems, LAMO, Rio de Janeiro 2017.

A Problem in Design Context

Preliminary research identified simple solutions to design problems on the mesoscale. We set the space limits between 3×3×3 m and 10×10×10 m, and thought about how to interact with the (few) variables during multiple generation through feedback. We outlined an interaction between the algorithm and the environment to open the "black box". Preliminary research identified similar situations among techniques, variables and contexts. We looked for applications of these techniques to public spaces, shelters, pavilions and constructive systems. By setting a boundary in the methods concerning the tools and the computational processes, we identified a search space and factors that interfered with this search, from mere generic to applied search.

We set up the workshop for undergraduate and postgraduate students, practitioners and professors, of different origins, in eight groups of three. They all learned to apply the different techniques, led by each tutor, and then we carefully selected 2 groups per technique. The participants' diversity of backgrounds and knowledge gave us the certainty to use visual programming with Grasshopper. This allowed implementation of generative algorithms without the drawbacks of learning a textual language, while its open policy enabled access to a great number of software add-ons for experimentation (Bueno, 2016).

CELLULAR AUTOMATA. Cellular Automata (CA) is a system that operates locally, as the state of the neighbours' cells, in each interaction, defines the state of each cell. John von Neumann and Stanislaw Ulam

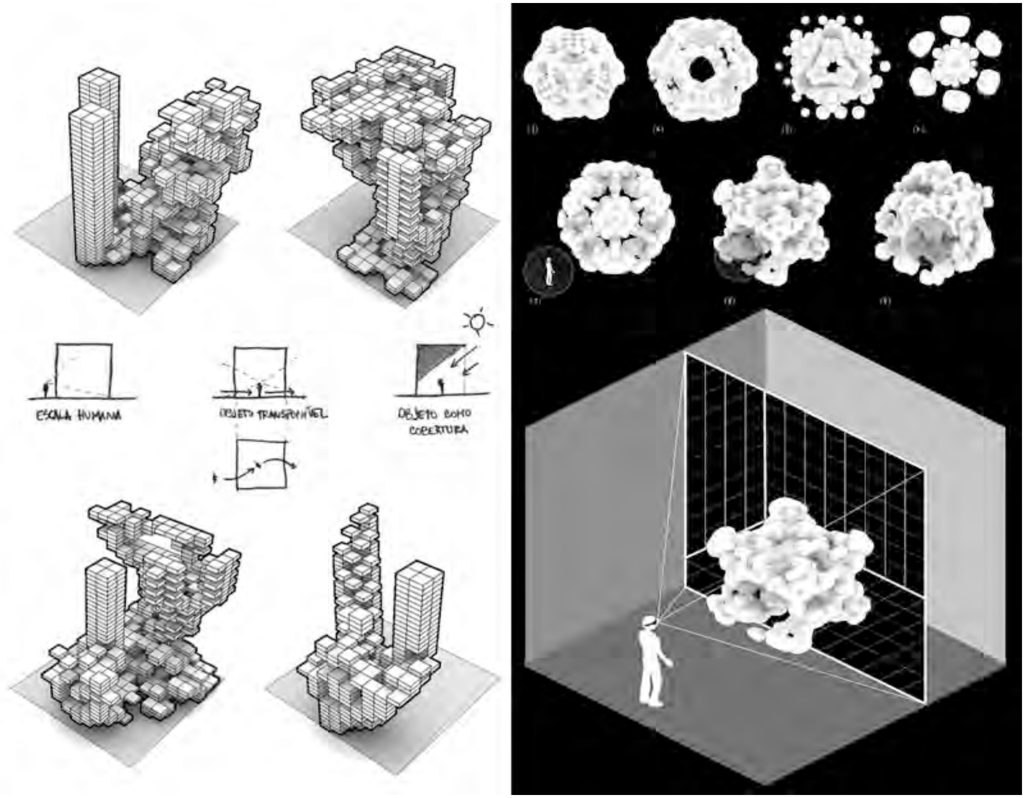


Figure 2
Cellular Automata (CA) proposals, Estranging The Context, architectural elements that inhabit the movies films, group: Thatilane Loureiro, David Mendonça, Eugênio Moreira (Left), and The Virtual Cocoon a three-dimensional CA that produces a four-dimensional object to be explored in Virtual Reality, group: Nicolle Prado, Isadora Tebaldi, Emilio Marostega (right)

developed CA in the 40s, and, since then, have been applied in a wide range of fields, such as Computer Graphics or Cryptography. Despite CA's ability to create form, it has few applications in architecture. According to intuition, a system with simple inputs using simple rules would produce simple behaviour. CA defies this conception, as it can produce across the range from simplicity to emergent complexity, as demonstrated by Wolfram (2002). CA can produce emergent and complex results.

In the workshop, CA's high degree of unpredictability required introduction of the idea of Form-Making, instead of Form-Finding. This is an alternative to contemporary rational trends that argue that simple quantitative criteria - such as environmental performance, material use, and cost reduction - should determine the architectural form. (Carpo, 2012). We invited the CA participants to analyse the spatial and aesthetic qualities of each configuration, in each recursion, and how they interacted with the system. There is no feasible way to foresee exactly how to change a rule to affect the product. Therefore, designers interact in a ludic way with the system differing from Albertian total control of the drawing. Participants approach the form-making algorithm in a playful horizontal way, supported by previous research about CA and computational morphogenesis to handle complex phenomena (Sardenberg, 2013).

CA Results: The approach diverged from simulating physical reality to focus on design as cultural practice. The first team used CA form-making to produce architectural elements to inhabit cinematographic contexts. Each project was conceived according to a specific genre (i.e. science fiction, comedy and horror), as an installation that responds to the film and changes it simultaneously. The second team, "Virtual Cocoon", used three-dimensional CA to produce a four-dimensional object that interacts with Virtual Reality. Usually we use a series of cubes side-by-side to represent 3D-CA. However, VR enables the user to interact with virtual objects according to his/her movement, in an immersive cocoon.

L-SYSTEMS. LS research focuses on literature, but especially on its technical implementation. LS are symbolic systems capable of generating growth structures, based on the ability to rewrite rules recursively. The biologist, Aristid Lindenmayer (1925-89) invented LS to describe the growth of simple species, such as bacteria and algae. Three concepts are embodied in this technique: (i) the initial axiom or seed, which represents the initial state of the system; (ii) the production rules applied to transform the seed, through (iii) recursion, a repetitive computational method that, in each generation, recalls the previous one.

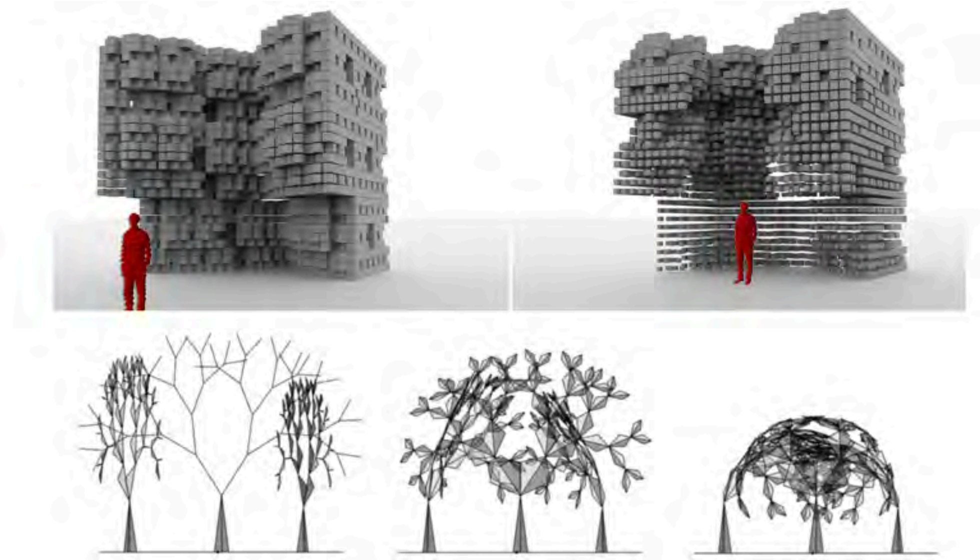
Originally, LS are formal deterministic systems, as the rules are context-independent. Being deterministic, there is one, and only one, substitution rule for each letter of the alphabet. In order to extend this technique, we searched for methods in visual programming to develop context-sensitive LS, allowing them to evolve from generating a single artificial plant to different species over time. The reference for LS design is the book by Prusinkiewicz and Lindenmayer (1990), and the articles by Fisher & Herr (2000) and Agkathidis (2015). As practical experiments, we sought diverse research, but especially the practical experiments by Coates (2001). While working with Grasshopper, we evaluated different LS addons like Rabbit (Dimitrova, 2016), which has an interpreter that translates the code into turtle graphics. We found that this interpreter accepts only letter symbols as input and is deterministic. Therefore, we looked for recursive loop applications that enabled non-deterministic or stochastic LS. Hoopsnake, cited by Sedrez (2013), was not very intuitive and had limitations. We also tested Loop (Turiello, 2013), and, finally, Anemone (Zwierzycki, 2015). The latter is the most intuitive; and during loops maintains the data structure and has an expandable list of data paths, enabling parameter value change in each generation. Anemone enabled response to external factors in each generation, implemented with turtle movement.

LS Results: The first proposal developed in the workshop was "Menger Revisited", and the second, "Hugging Trees". The possibilities explored are complementary. The first revisits the Menger sponge, proposing interactive, recursive transformations: the fractal changes according to the user, in a virtual space. It went beyond the classical Menger sponge by breaking the symmetry in unpredictable, yet relational, ways, without losing self-similarity. The second proposal develops tree-like structures that reconfigure themselves according to human position, changing the branch angles and planes of rotation accordingly. The percentage of randomness that affects tree movement is associated with external factors. When the user reaches the centre, the trees embrace him/her. The first solution has potential for VR and can output data for augmented reality. The second, despite following tree stereotypes, possesses a feasible mechanism for a physical articulated structure.

GENETIC ALGORITHMS. A finite set of rules and operations defines GA that simulates the combination of individual characteristics of the same species, to select those with the best environmental fitness. The algorithm's structure considers the main mechanisms present in the evolution of species as genetic inheritance, random variation (crossover and mutation) and natural selection.

We relate GA with the broad use of engineering to optimise structures and components. The use of

Figure 3
Menger Revisited, showing recursive system variations triggered by user proximity. Group: Fernando Lima, Aurélio Wijnands, Maria Eloisa. Hugging Trees, showing the fractal movement of trees as the user approaches. Group: Núbia Gremion, Erick Bromerschenckel, Daniel Wyllie.



GA in design is frequent in spatial planning optimisation and form generation. Although it is an optimisation method, we can use it as a generator mechanism to assist the designer in exploring the solution spaces, to obtain creative, emergent and unexpected results. In this context, the algorithm is set to obtain favourable solutions independently of the optimisation level attained, guaranteeing a flexible choice among the solutions generated. The main references are Holland (1995) Bentley (1999) and Mitchell (1999). Grasshopper has a genetic solver, Galapagos. However, the number of design problems it can tackle is limited (Rutten, 2013). We used the add-on, Biomorpher (Harding, Olsen, 2018) that allows the designer to interact with the algorithm during its execution. The designer selects the "parent individuals" from quantitative (optimal) and qualitative (aesthetic) criteria, directing the evolutionary process, as the "individual parents" will be crossed to generate "individual offspring".

GA results: The projects developed were "Evolutionary Aggregation" (EA) and "Dwell Debris" (DD). They adopted as criteria: shade, contact with the ground and formal arrangement. As a strategy for structuring the GA, EA distributed the components in a regular 3D grid, ensuring modularity and orthogonality. The DD authors opted to anchor components in a random cloud of points, creating an irregular arrangement. In both situations, the teams subtracted the original grids with additional voids, but using different components. EA defined a single component with freedom of rotation on the central axis. DD defined four components that rotate on their axis, all generating a diversity of solutions. EA programmed the GA to find solutions that had the largest contact among components and the largest projected shadow. The DD team searched for the greatest number of intersections among components, the greatest volume on the ground and the least shade. The participants used the add-on, Biomorpher to cause evolution of formal solutions with human intervention.

SHAPE GRAMMARS. SG uses encoded abstract formalisms that limit its use to specialists. These formalisms also limit free interaction in the form of de-

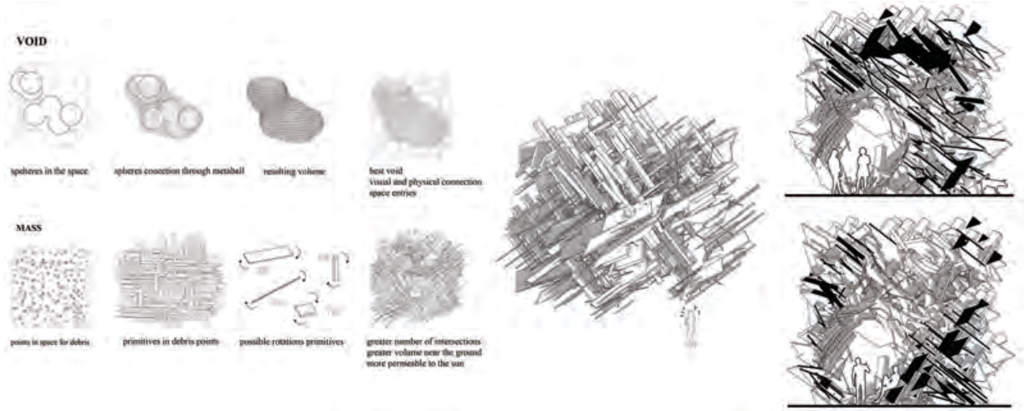


Figure 4
Group DD strategy and solutions. Group: Anael Alves, Loan Tammela, Felipe Lannes. Group EA strategy and solutions. Group: Luciana Gronda, Igor Machado, Monique Cunha, Wellida Coelho.

velopment. SGs have different natures as descriptive and generative grammars (Garcia, 2016). To bridge this gap, we developed a more intuitive interface in visual programming, relying on earlier Stiny texts to structure the definition. We identified a recurrent description that we organised into the triple ordinate:

$$G = (v, r, d)(1) \qquad (1)$$

where G is grammar, v vocabulary, r rules set, and d derivation. The algorithm concatenates three sets, maintaining each variable's internal independence and the set's co-ordination. The loop uses v as input, applying the r rule indicated in d, accumulating the result in v. While v and d are simple lists, r is more complex. The initial axiom has two shapes, setting the initial and final form, memorising the Euclidean transformations, and then applying them as input shape. As holdbacks, the definition operation cannot recognise the shapes used. The next step would be recognising emergent forms. The algorithm's simplicity encouraged participants to develop their own definitions.

SG Results: The first team used SG that relates a façade composition with music notation, while the other designed a shelter. They adapted the initial algorithm, exploring the generation of diverse designs. If we know the result of a rule application, it is easier to predict the emerging phenomena. Thus, in the SG definition, we knew the initial and final form, which facilitated the interaction. The derivation played a fundamental role in SG. However, SG teaching focuses on shapes and rules, how to change the derivation that needs to incorporate uncertainty that remains obscure. Full randomness probably leads to meaningless design, and some randomness can still generate meaningful results. This requires encoding the derivation data, organisation (data tree) and the random derivation paths.

RECURSIVE LOOPS

Beings evolve interacting with the environment in a continuous process in time. For generative systems to evolve, in addition to interaction and selection mechanisms, we need recursion. The creation of such repetitive cycles was limited to those mastering formal computation. By introducing recursion in different design situations, using visual programming, we pointed out how systemic interaction can generate evolution.

TECHNIQUES AND INTERACTION

The interaction between CA rules and the context happens after the form generation, when the user can interact in virtual reality with the CA. In LS, we open the system boundaries to accept interference

Table 1 Generative Techniques in Design (CA, LS,GA,SG): Purpose, Scope, Challenges, Outcomes and Interference. Interference is based on the results of the empirical tests of the workshop, envisioning future possibilities.

Generative Design Techniques

	Purpose	Scope	Challenges	Outcomes	Interference
CA	Creation of multi-dimensional objects and a (large) variety of results that can be context-sensitive.	Form-finding and form-making; Growth patterns; Self-replicating machines; Social application, data models.	Relation between the local rules and global results. Unknown or undefined system boundaries. Predictability.	Emergent spatial arrangements and typologies that can be context-sensitive. Undesired, strange or chaotic results.	Interference achieved in virtual reality. Possible Interference with growth processes that relates local-global results.
LS	Generation of form, structure and patterns. Spatial layouts. Morphological designs.	Symbolic nature (abstract rules) Closed set-rules: deterministic. Open set-rules probabilistic or stochastic.	Generates fractal patterns, of a graphical nature that are in a closed system. Difficult preview /change global form.	Spatial arrangements, roads, networks and terrains; Evolutionary systems through interaction.	Achieved recursion in-cycles. Control dynamic structures (Digital, physical, but can be also biological).
GA	Optimisation; Improve design; Multiple design alternatives. Meeting fitness criteria.	Combinatorial and morphological designs. Disruptive innovation.	Difficulty to translate problem into representation. Fitness function, genotypes phenotypes, requires experience.	Optimised, solutions. Multiple design alternatives. Component-based combinatory solutions. Might cope CA,LS,SG	Interference with each generation, associating quantitative (numerical) and qualitative criteria using Biomorpher.
SG	Generation or description of form using rules.	Shape nature (shape rules) Rules to construct a family of forms.	Formal language difficult to master. Self-centred form definition. Difficult use non-probabilistic reasoning form-finding	Exploratory geometrical design; Solutions for complex combinatory problems. Ruled based design.	Initial and final form set, so interference only rules derivation. Possible interference using cumulative rules and evaluation.

between the user and the context, in every generation, using scholastic algorithms. In GA, we overcame the limitation of a blind system of blind optimisation by allowing the user to interfere in each generation, introducing qualitative criteria that change evolution. In SG, we broke the closed system, allowing the user to affect, not only initial and final form, but also interfere with the derivation rules.

Visual programming contributions

- A cellular automaton including a library of context-specific objects;
- 4D-CA with VR visualisation;
- Responsive stochastic L-systems;
- Multi-objective evolutionary optimisations (geometric max shade optimisation), possibility of qualitative decisions during iterations;
- Automation shape grammars (Grasshopper);
- A 3D graphical music grammar.

However scarce, the workshop results reveal the gap between tools and processes. Singh Gu (2012) compared generative tools to integrate them in a "Computational Design Framework", a valuable contribution to research. However, besides the literature survey, is necessary to test them in context. We used empirical knowledge to fuel design thinking about both tools and design processes. Above we present a synthesis, explaining how we interfere with the tools rules, envisioning future possibilities.

GENERATIVE TECHNIQUES AND DESIGN RESULTS DISCUSSION

The techniques described in this article have existed since the 80s, but their implementation is slow. Previous formal approaches failed to translate the tools into design methods. We proposed a framework grounded on Design Thinking and complexity, to implement contextual interference with recursive cycles. Finding an alternative to formal computation, using loops in visual programming, we show how to interact with tools using recursion. Anemone proved adequate for recursive processes, in both data replacement and incremental growth, allowing designers to interfere between the cycles. Biomorpher demonstrated the value of human interaction with an evolutionary process, working as input of qualitative criteria. We found recursion and selection mechanisms have potential to develop systems that may evolve in the desired direction using Visual Programming. However, this requires technical improvement of the loop processes and further development of the solution selection mechanisms.

With the increase in Information. the problem space augments. With the introduction of interaction in time, with a selection mechanism, and enabling the system to learn in the future, we expect to enlarge the solution space. This would follow the Von Neumann self-replicating machines that can extend AI. Finally, the generative tools are several algorithmic methods, with their specificities. We must tame these algorithms and go beyond the dichotomy between techniques and methods (tools and processes). Only then can these algorithms be absorbed, both by the design thinking and by the maker culture.

Facing the fourth Industrial Revolution, this fusion of techniques reinterprets old methods: by introducing direct interaction and an increasing number of context-related variables, generative systems can deliver responsive designs. Generative methods can offer a symbiotic partnership between the designer and the system to expand architectural abilities skills. In the light of the fourth revolution, they can intertwine information, whether digital, physical or, in the future, biological.

Form Finding and Generative Systems

LAMO Seminar/Workshop Form Finding and Generative systems, Rio de Janeiro Federal University, 28 Aug to 7 Set 2017, Coordination Gonçalo Castro Henriques, Andres Passaro and Elisa Vianna. Tutors generative tools: Victor Sardenberg, Ernesto Bueno, Gonçalo Castro Henriques, Jarryer de Martino and Daniel Lenz. Our gratitude to PROURB for supporting the event and to all participants and collaborators, we cannot name here due to space limitations.

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A Generative System for the Terrain Vague

Transcarioca Bus Expressway in Rio de Janeiro

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The transport infrastructures are important elements in the cities, but, as there is a lack of planning, they tear through the urban fabric and leave empty spaces. Due to government and private disinterest, these spaces become vacant, forgotten and degraded. However, these extensive Terrain Vague offer new potential for urban use. To exploit this potential, we need methodologies that can offer personalised, extensive, feasible urban solutions. For this, we propose a computational generative system, following a 4-step methodology: 1) Site analyses and Terrain Vague identification; 2) Site classification according to parameters based on a ``visual grammar''; 3) Algorithm associating space properties with geometric transformation to generate solutions: namely transformative operations in public spaces, additive transformations in semi-public spaces and subtractive operations in semi-private spaces; 4) Solution evaluation and development, according to shade criteria, spatial hierarchy and volumetric density. With our own algorithms combined with genetic algorithms, we guided the evolution of 50 volumetric solutions. The exponential increase in information requires new methodologies (Schwab, 2018). Results show the potential of computational methodologies to produce extensive urban solutions. This research, developed in a final graduation project in Architecture, aims at stimulating generative methodologies in undergraduate courses.

Keywords: *Terrain Vague, generative systems, parametric urbanism, genetic algorithms*

INTRODUCTION: PROBLEM CONTEXT

The introduction of large mobility infrastructures in Brazilian cities in the last 10 years, such as express bus lines (BRT in Portuguese), have not only helped to improve the transport system, but also brought new challenges regarding how to organise the urban tissue. The impact of these infrastructures on the periphery, in densely populated areas with low property values, plus a lack of planning, result in poor or abandoned spaces. The introduction of these infrastructures into the urban fabric produces urban voids, designated as *Terrain Vague* (Pereira, 2011).

Terrain Vague also represents a new hope due to its transformative potential. To express this idea in this work, we use the original French expression, *Terrain Vague*, as translation would restrict its meaning. Solá-Morales (2002) argues there is no English translation for the word. While in English, the word terrain refers to agricultural and geological concepts, the French relates to an expandable vision, as it is connected to the physical idea of a portion of land that has a potential condition to aggregate value to the city. But it is the second word, vague, that in English is only something empty, unoccupied, lacks the French sense of free, available and willing to establish a physical status. The French meaning also represents indeterminate, imprecise, blurred and uncertain, giving a temporal idea to the space.

The *Terrain Vague* (used here as plural) exist in areas of the city without function or social content. They are located in places connected by the infrastructures, but do not fully fulfil their social and economic functions, as they are occupied by structures without use or activity, and are vacant or empty (Borde, 2013). In spite of being areas of urban decay, they are also areas with potential for activism and social transformation.

Proposals for the *Terrain Vague* are scarce, considering the diversity, complexity and predominant presence of such land in contemporary cities. Besides conceptual studies, there are only a few studies proposing design solutions for these places.

There are political and economic factors involved in this process. The *Terrain Vague* are a by-product of property market operation, the private agents' behaviour and the public policy agency. It depends on the negotiating capacity and flexibility offered by future dynamics, present in political, economic and social objectives of the various planning models (Borde, 2013).

Therefore, the scope of the problem is vast. This work has no intention to solve all the *Terrain Vague* issues, but to contribute to developing a design methodology to act on the urban landscape.

HYPOTHESIS

We developed a generative system, using computational tools, to produce customised solutions for a set of empty spaces. Given the scale and number of *Terrain Vague* and their particularities, an individual resolution method, designing site by site is time- and resource-consuming. Since there is no systemic methodology to address this problem, we developed one for an urban area crossed by the Transcarioca Bus Expressway, on the Rio de Janeiro urban periphery. We analysed the Transcarioca along an 8-km stretch, identifying *Terrain Vague* in this area, resorting to a "visual grammar" (Bradley, 2010) to summarise their characteristics.

We chose a specific *Terrain Vague* site, and assessed the scale of the destroyed residual spaces that had not been reconstituted (Ferrara, 2000 and Borde, 2013); this selection was necessary to feed and test our generative system.

METHODOLOGY

We organised the methodology into four steps: Analysis, Classification, Generation and Selection. The first step focused on the macro scale, understanding the patterns of the environment, to identify and enumerate possible areas of action. In the city registries, we identified 90 areas, and grouped them according to their characteristics and relationship with the macro environment.

In the second step, we classified the group in more detail, and decided to focus attention on 50 areas to test the development of the generative system. To classify the areas, we developed a "visual grammar" derived from the iconic representation of the book, "Phylogenesis" (Zaera-Polo, 2003). In this book, the author identifies the formal generation of his design proposals according to a "visual grammar" that classifies them into different species, which we will describe later in detail. Although the methods used in Phylogenesis are analogue, it is possible to see an evolutionary sense in the proposed method, which we can implement with the support of computational methods. To define a "visual language", we identified common urban properties in the *Terrain Vague* and organised them into six categories (according to orientation, main axis and number of floors).

In the third step, we defined an algorithm based on these categories to generate geometric solutions for the 50 cases selected. The goal of this grouping was to automate the design process for all the *Terrain Vague* that have similar problems, albeit in different contexts. In the system, we defined three geometric operations according to three spatial types. The geometric operations were based on the work by Mari (2017), and each corresponded to the following spatial types: 1) public spaces, addressing transformation of spaces to be used as urban squares, defining the ground according to green and paved areas; 2) semi-public spaces, addressed by the addition of geometries to match the surrounding constructions. Thinking of using these nodes as activity-concentrating places, the system seeks the best position for the proposed geometries, according to shade, pavement lengths and free spaces; 3) semi-private spaces that subtract geometries from the total volume. The system evaluates the position of the subtractions according to the density of the operation, shade and open spaces. To develop these processes, we used visual programming (Grasshopper).

In the fourth and last stage, we evaluates the results obtained in the previous phase and then derived solutions. As it is an interactive process, the generation of solutions becomes a cyclical process, in loops, and so we used genetic algorithms to improve the results in this interactive process. Firstly, we relied on the concepts of Chiang (2017) and Alexander (2013) to define three criteria. The first criterion (Shade) analyses the total shaded area generated by the volumes in a site's open spaces (in the Rio de Janeiro region, shade is an invaluable asset). The second criterion (Open Space Hierarchy) compares the volumes generated and the resulting open spaces. The third criterion (Compactness) measures the volumetric linearity of the proposals. After generating solutions, the architect, like a geneticist, evaluates them according to each site's requirements. To influence the evolution of the results in an interactive way, we used the plug-in, Biomorpher that allowed us to intermediate genetic algorithms of quantitative development, with qualitative criteria by interfering with the selection of results, in every generation, considering multi-criteria analysis (Harding, 2018).

Analysis
We analysed an 8km region, bounded by the Penha and Irajá districts on the Rio de Janeiro periphery. From the analysis and identification of the environmental patterns, we selected 90 areas and divided them into 7 groups according to their relationship with the surroundings and intervention possibilities. These areas were:

Public squares: we identified 11 spaces cut and fragmented by BRT, most enclosed with walls.

Underneath infrastructures: 3 unused areas under viaducts.

Residual spaces: 50 buildings in ruins, not rebuilt. Some of them were illegal rubbish dumps or car parks, and the remainder enclosed with walls.

Walls: 8 buildings with blind façades and viaducts walls, surface and underground railways.

Idle structures: 5 abandoned structures, such as old service stations and unfinished houses.

Roundabout access: 8 cases that corresponded to intersection spaces between two or more roads.

Footbridge: 5 cases of long, narrow, thin, unsafe footbridges, some of which had fragile structures, while others were unsafe.

We started the study by addressing one of these spatial classifications, the Residual spaces, as they are greater in number, in many areas and contexts, but have similar problems.

Classification
The following step represents the beginning of the generative system: how we defined it and how many variables we considered. The Classification uses as its main reference the book, "Phylogenesis" (Zaera-Polo, 2003), which presents 36 architectural projects of the Foreign Office Architects (FOA), documenting

the geometric primitives that generated the external form of each of the projects, grouping the projects into categories. To represent the "species", they use a "graft" that branches according to the categories and the projects. They illustrate these 7 categories with icons defining a "visual grammar" that we have reinterpreted and used to define rules to generate proposals.

Dividing the term "visual grammar", the first word, visual or visual language, consists of an alphabet of numbers, dots, lines and shapes, which can be organised into direction, tone, colour, texture, dimension, scale, and movement. On the other hand, the second word, grammar, is used to refer to the system and structure of a language. Considering that the elements of a visual language, as well as all languages, are organised by a grammar (Bradley, 2010), the term "visual grammar" refers to the structure of the visual elements of a language.

In this work, the vocabulary consists of visual elements of lines and shapes, forming icons in order to represent the urban parameters and to facilitate the communication methodology.

The classification defined 6 categories and 16 subcategories. Each category corresponded to an urban variable common to all the cases studied; in each subcategory, we used an icon to illustrate this variable.

Category a. Type of Space. *Goal:*To separate sort public, semi-public and semi-private spaces

Understanding that the urban infrastructures have been detrimental to the public spaces, some of which were already precarious, this work thought of introducing new places with different levels of use and activities. Firstly, we classified the cases for public use in relation to the existing local public squares. After this, we divided the remaining cases into semi-public and semi-private spaces. As Torisson (2008) defined, the first type of space is a private space accessible to the public, for instance a shop and a restaurant (nodal points or commercial concentration). It is open to the public, but has a certain private character. We can define the second as a space controlled by a front door access. They are not private because although closed they are accessible to outsiders, they are not public either, as cinemas and theatres (cultural activities).

Urban variable: distance between public squares and nodal point selection.

Subcategory:

EXTERNAL:

Cases that have potential as a square or public space. We looked for squares within a 10-min. walking distance, or 400m, to define new squares in the empty spaces.

Cases that have nodal point and semi-public space characteristics. We organised 50 cases in a list, setting a nodal point every 400m. These are activity-concentrating points.

INTERNAL: The remaining cases had semi-private spatial characteristics.

Category b. Layer Type. *Goal:* sort the cases by the number of floors

Urban variable: total building height obtained by the difference between the buildings and the ground level according to the Rio de Janeiro database.

Subcategory:

SIMPLE EXTERNAL: ≤ 1 floor.

COMPOSITE EXTERNAL: ≥ 2 floors.

SIMPLE INTERNAL: ≤ 1

COMPOSITE INTERNAL: ≥ 2 floors.

Category c. Predominant Orientation. *Goal:* sort the cases by the number of accesses

Urban variable: number of accesses.

Subcategory:

UNIDIRECTIONAL: one access.

BIDIRECTIONAL: two accesses.

TRIDIRECTIONAL: three or more accesses.

Category d. Predominant Axis. *Goal:* sort the cases by predominant axis.

Urban variable: area squared and total height. It is the relation between the heights squared divided by the case area

Subcategory:

HORIZONTAL: the area is larger than the square of the total height.

VERTICAL: the square of the total height is larger than the area.

Category e. Geometric Operation. *Goal:* sort geometric operations by categories.

Urban variable: insolation studies, total building height, distance between local public squares and nodal point selection.

Subcategory:

TRANSFORMATION: "SIMPLE EXTERNAL" with public square characteristics. Geometries subjected to transformative actions, such as bend, tilt, divide, twist, overlap and rotate.

ADDITION: "EXTERNAL" with nodal characteristics. Geometries subjected to addition, such as expand, extrude, inflate, branch, join and move.

SUBTRACTION: "INTERNAL". Geometries subjected to the subtraction, such as sculpt, compress, fracture, chamfer, tighten, inlay, extract and inscribe.

Category f. Contextual Relationship. *Goal:* sort the cases by proximity to BRT stations.

*Urban variable:*distance to BRT station.

Subcategory:

INDEPENDENT: BRT stations beyond a 100m radius

DEPENDENT: BRT stations within a 100m radius.

To finish the classification, we represented the data using three types of visualisation. We used a different colour for each case and presented a summary of its category and adding an icon (visual grammar).

We first used a quantitative map illustrating the cases by categories and subcategories, showing the quantity and percentage within each classification. The data is presented in a clockwise direction, starting by identifying the case number, the number of floors and the area squared, and then connecting it to the corresponding subcategories through lines.

The second map we used is a geographical map that illustrates all the case contexts with their respective classification summaries. Some cases are related to the buildings of the book, "Phylogenesis" (Zaera-Polo, 2003) that have the same order of classification.

The third map we used is qualitative. Each branch division sorts the cases according to the previous classification. For example, in the first column, the EXTERNAL cases go upwards and the INTERNAL

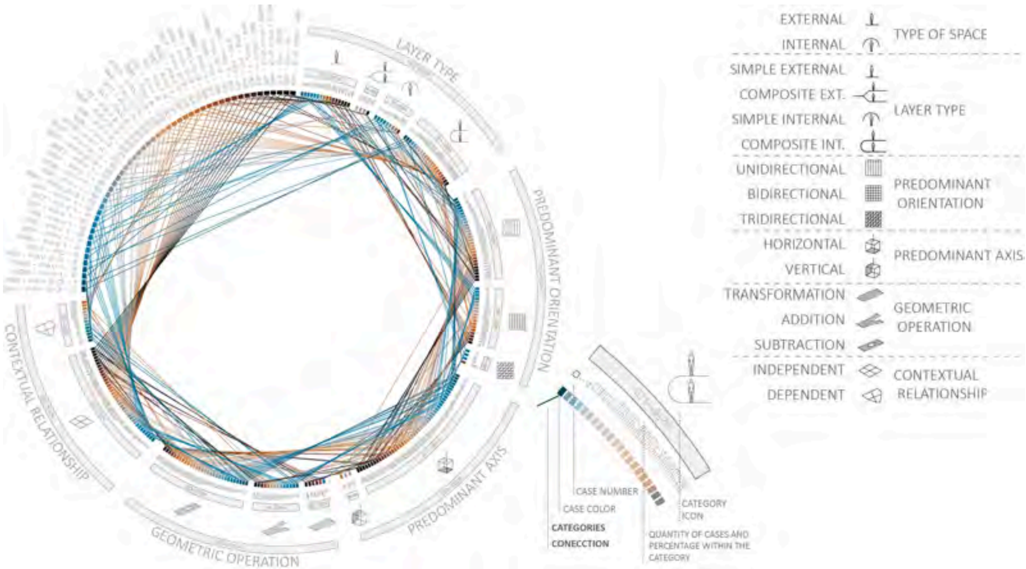


Figure 1
The Qualitative map

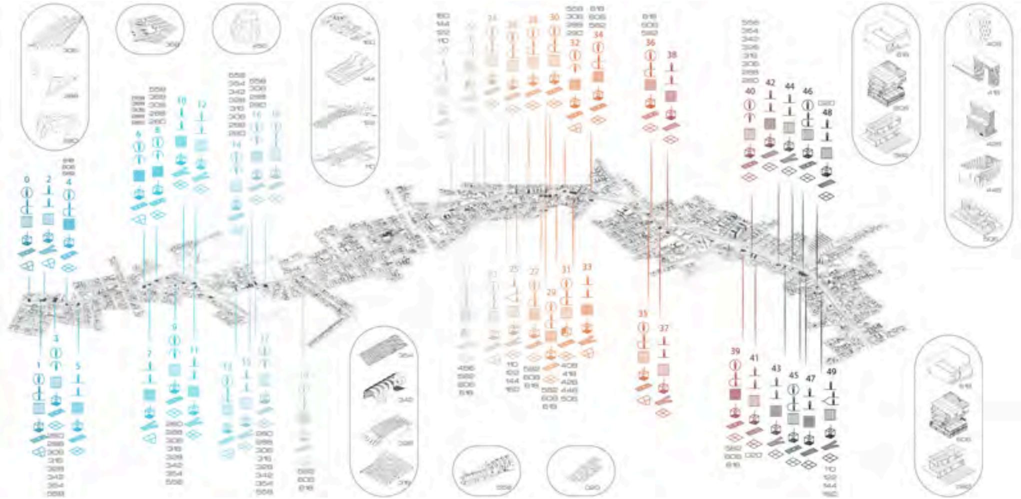


Figure 2
The Geographic map

downwards. The Generation step below presents a display of the branches.

Generation

Based on the categories, the third step documents the algorithm construction, illustrating the geometric development of the solutions. The Generation uses as reference the book, "Operative Design: A catalogue of Spatial Verbs" (Mari, 2017). The book presents a series of operations used as "kick-starters" for compelling spatial exploration. It uses three main verbs, displace, add and subtract, which we reinterpret and develop in this work.

The next graphs are related to the qualitative maps by their columns, in order to illustrate the changes in the algorithm. Each branch created corresponds to a new rule.

Transformation, in public spaces. The first process transforms the ground; modifying, scaling, shortening or extending it. Column I displays the type of operation and represents the degree of deformation according to the user's need. For instance, with the majority of children in the surrounding area, the system works with more profound transformations on the ground. Column II configures the grid to apply in the proposal. As initial grid possibilities, we established a striped division with a minimum width of 3m. Column III describes the stripe orientation. We decided that their direction would always be towards the façade of the BRT lane. Column IV combines the stripes and the flat spaces, paved areas, or transformed green areas. We can transform each space into three types of wave frequency, represented in Column V, and it has a direct relation with Column I, the user's need. The last line shows some of the results.

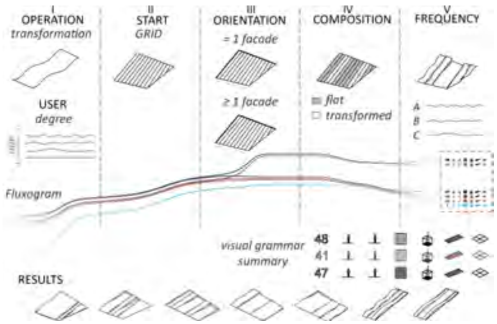


Figure 3
Transformation process

Addition, in semi-public spaces. The second process addresses the addition of geometries to match a volume. Thus, Column I shows the type of operation and the volume offset according to the user's requirements. For example, if the proposed site has narrow pavements, the system can limit the occupation volume, in order to increase the space outside. Column II configures the grid to apply in the proposal and the number of floors. We set as an initial grid, a 3mx3m cell division that we replicate in the upper floors. Column III describes the grid orientation. We decided to always orient it towards the façade of the BRT lane. Column IV corresponds to the merged cells on each floor, and Column V represents the volume formation. The last line shows different results.

Subtraction, in semi-private spaces. The third process subtracts geometries from an initial volume. Column I shows the type of operation and the subtraction amount according to the user's requirements. For example, if the goal is to generate proposals with large openings, the system calculates bigger subtractions and in a greater number. In Column II, we configured the maximum occupancy volume and the type of subtraction according to the number of floors. In one-floor cases, we split and trimmed the volume; and in two or more floors, we used multiple-size cubes to subtract the volumes. Column III describes subtractive geometry orientation. As an initial experiment, we established orientation of all the geometries perpendicular to the corresponding façade. The value of orientation angles corresponds to the access case number. Column IV illustrates the subtraction process, and Column V represents the volume shape. The last line shows some proposal results.

As seen in the Generation step, each geometric operation has a different algorithm logic, based on the category and subcategory we had defined previously. Therefore, we made this process to start experimenting with volumetric solutions, so that they could be refined with the system development. As it is an interactive process, the solution generation is a cyclical process, in loops, using genetic algorithms to improve results (Fischer, 2000). Next, we introduce the selection process.

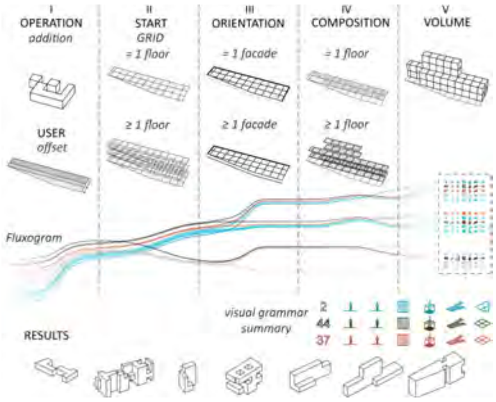


Figure 4
Addition process

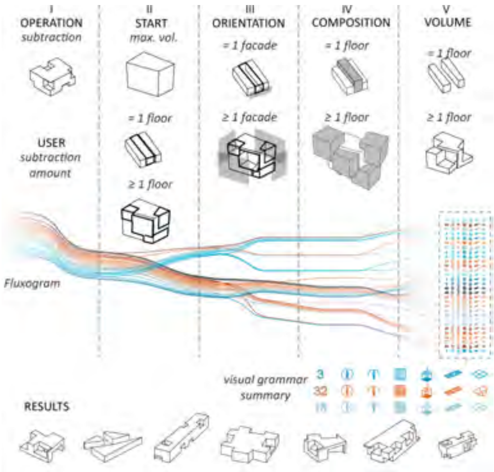


Figure 5
Subtraction process

Evaluation and selection

In the fourth and last stage, we initiated the evaluation and selection of the multiple results generated in the previous steps, in order to filter and identify the best proposals. Firstly, we created three analytical criteria so the proposals are on a normalised scale.

Thus„ we could compare the values. After this, we evaluated the proposal's quality.

We used the plug-in, Biomorpher that allowed us to interfere with each evolutionary cycle, by introducing qualitative criteria. The genetic algorithms for optimisation rely on quantitative values, so Biomorpher allowed us to introduce qualitative criteria to include in the next development cycle according to multi-criteria (Harding, 2018).

Criteria. We defined three criteria according to three characteristics of the cities: shade, open space hierarchy and urban density. This step used as references the article, "Measuring Neighborhood Walkable Environments" of Chiang (2017) and the book, "A Pattern Language" of Alexander (2013). The article discusses walkable environments in the city, and we used its concept of street connectivity and pavement quality to evaluate if a proposal encouraged alternative paths within the site. The book demonstrates three scales of city patterns: towns, buildings and other constructions; and it shapes the environment according to these patterns, in order to solve a stated problem. We based our methodology on towns and building patterns, where discussion about the relation between public/private spaces and the volumetric composition of urban areas takes place. We used these urban concepts to measure the dimensions and scales of the volumes proposed and their open spaces.

Therefore, to choose the best solution, we evaluated each characteristic of the solutions generated.

Shade (S): Quantifies the larger shaded area in summer and the smaller shaded area in winter produced by the volumes generated in its open spaces.

$$\frac{(1-SU)x2.5+WIx0.5}{3}=S \qquad (1)$$

WINTER-WI=Σpt/ΣptSUN; SUMMER:SU =Σpt/ΣptSUN

Open Spaces Hierarchy (OSH): measures the hierarchy of the open space area in relation to the volume area generated, through crossing or access to the site, proportion and dimensions of the proposed open space.

$$\frac{0.5xCRO+1.75xPOS+1.75xDOP}{4}=OSH \qquad (2)$$

CRO= Number of crossings; POS = Proportion of Open Space (open space area/total area); DOP = Dimensions of Open Spaces (width/length)

Compactness (C): measures the linearity of the geometry. The larger the C, the more compact and linear the volume, and the smaller the façade area.

$$1-\frac{Asur}{Vol}=C \qquad (3)$$

Asur = Area of Surfaces; Vol = Volume

Evaluation. The quality criteria is associated to the evaluation of the geometry generated. In the context of multiple generation possibilities, the designer makes the analysis and observes the proposal's fulfilment to decide. To make it clear, we displayed four examples of geometric operations to develop the initial results.

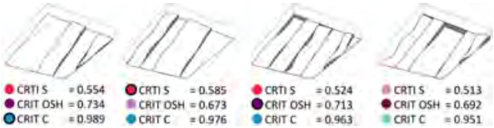


Figure 6
Transformation, in public spaces

Transformation, in public spaces

1. Higher C criteria: more compact geometry
2. Higher S criteria: more shade in the straight stripes
3. Higher OSH criteria: more rectangular / narrow open spaces
4. Lower S criteria: more insolation with straight stripes.

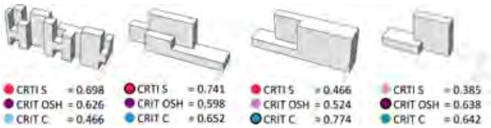


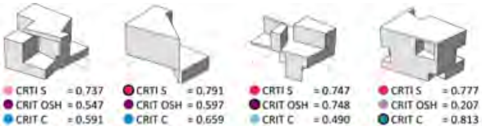
Figure 7
Addition, in semi-public spaces

Addition, in semi-public spaces

1. Lower C criteria: more sinuous geometry
2. Higher S criteria: more shade in the open space
3. Higher C criteria: more compact geometry

4. Higher OSH criteria: bigger open space

Figure 8
Subtraction, in semi-private spaces



Subtraction, in semi-private spaces

1. Lower S criteria: more insolation in the open space generated
2. Higher S criteria: more shade in the open space
3. Higher OSH criteria: bigger open space
4. Higher C criteria: more compact geometry.

When it comes to the transformation process, we focus on the topographic deformation, the S criteria (Shade) is naturally lower, and less decisive in the selection of the final solution. We evaluated these surfaces using OSH criteria, prioritising narrower greener areas. Precisely because they are public squares, this criteria in relation to the other geometric operations should have the highest evaluation to prioritise green spaces. We measured the C criteria by the ratio between the surface area and the total volume. Referring to topographies, the criteria resulted in high values with little variation, making the selection process difficult.

As for the addition process, the S criteria analyses the shading of the open spaces we proposed. The values have variations and they are consistent with the total area of the open spaces. The OSH criteria evaluates the open space proportion in relation to the total area; to create new accesses, contributing to new routes in the city. However, the values obtained still had little variation. We measured the C criteria by the ratio of the surface areas to the total volume. The values achieved were consistent with the analysis.

Referring to the subtraction process, the S criteria analyses the shade of the open space solutions. As they are subtracted volumes, their criteria values should be higher, because they provide greater sun protection. The OSH criteria evaluates the proportion of open spaces in relation to the total area. The values obtained are consistent with the analysis. W measures the C criteria by the ratio of the surface areas to the total volume area. The values obtained were consistent with the proportion of proposal subtractions.

As a first approach, the results are significant, although the algorithm could be improved. This experiment proposed and tested a methodology to improve the results.

Selection

In the last step, we evaluate the solutions to satisfy the requirements. As an exploratory model, we selected one proposal for each geometric operation and briefly illustrated their uses.

RESULTS

We created and developed a methodology for a generative system to find solutions for the *Terrain Vague*. We analysed and mapped 90 sites. We proposed a visual grammar with 6 categories and 16 subcategories that codifies urban variables to generate occupation solutions. We developed an algorithm associating three geometric operations with three types of space: transformation in public spaces, addition in semi-public spaces, and subtraction in semi-private spaces. Associated with this, we developed a recursive method to generate solutions, improving them in cycles. The volumes were selected by 3 criteria: Shade, Open Space Hierarchy and Compactness of the proposals. Finally, with our methodology, we produced a family of 50 site solutions.

DISCUSION

We developed this research in a final graduation project in Architecture, which is not usual in Brazil, nor in most universities in South America. The University does not teach the knowledge that is necessary to develop such a system in the regular compulsory Architectural disciplines. It is only possible with a special interest and dedication to learning new subjects, in optional disciplines in conjunction with research workshops developed at LAMO, like "Defy-

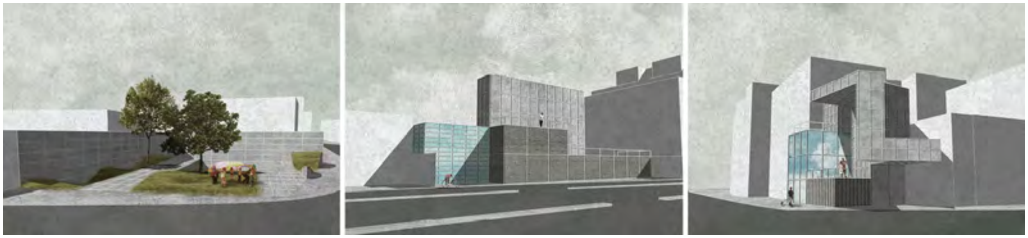


Figure 9
Transformation, Addition and Subtraction examples, respectively.

ing Gravity" (Henriques, 2015), and, more recently, "Form Finding and Generative Systems" (Henriques, 2018). The main objective was to make a generative system capable of generating multiple options. In this sense, the focus was on the development of a new tool rather than its accuracy for final solutions. Regarding the reviewers' comments, we would like to add that future research could also address the social concerns.

By defining geometric rules, the generative system produced unforeseen or unexpected volumetric solutions, expanding the design possibilities. This happened for two reasons. The first is because the demand includes a randomness factor, present in the dispositions and scales of the transformation elements, addition and subtraction. The second is the restriction of these elements, allowing interaction with the genetic algorithm through quantitative restrictions, Shade, Open Space Hierarchy and Compactness; and qualitative, volumetric composition, which the designer chooses.

The proposed methodology and the results obtained demonstrate the feasibility of developing a generative system. The research intended to be a proof of concept. In this regard, the criteria and values were not a concern per se or the centre of the research. Rather, we favoured development of an evolutionary system to generate families of solutions for the *Terrain Vague*, which we can improve in the future.

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Form-finding methodology as strategy for formative research in industrial design education

Experimental techniques for the early creative phases of the product design process

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The experimental work of Antoni Gaudí and Frei Otto have been the precedents of what is currently called form-finding, a methodology based on rules and physical forces of nature that promotes principles of transformation as a result of the relationship between form, material and structure. This text shows the first results of the research titled as Form-finding methodology as strategy for formative research in industrial design education, with an empirical-analytical approach through action-research based method and using collaborative-participatory tools. As a result of the analysis of different cases in the first stage of the research, a basic methodological proposal is made, this methodological proposal is aimed to find new research possibilities for the identification of morphological characteristics to be used in design projects in the early creative phases (ideation and experimentation); the methodological proposal stages are the following: selection of technique, design of the experimentation, experimentation, analysis and discussion.

Keywords: *Form-finding, Experimental morphology, Industrial design education, Formative research, Action-research*

INTRODUCTION

Jacob (2014) said that the organization of living systems obeys a series of principles, both physical and biological: natural selection, minimum energy, self-regulation, stepped construction, among others. The forms in nature are diverse and heterogeneous, they are the result of different forces that have shaped them for millions of years in a constant, changing and unpredictable process; Sir D'Arcy Thompson in his book entitled On Growth and Form makes a study about the incidence of natural forces in the form of plants and animals, in that research he affirms that the form is a diagram of forces. But these constant changes and transformations occur in the context of physical, geometric and material constraints, Wasenberg (2013)said that the world around us is diverse, creative and changing, but it exists in the context of restrictions and rules, because not everything can persist and remain in this reality.

Between the second half of the 19th century and the beginning of the 20th century, Antoni Gaudí, an innovative architect and artist, broke the paradigms in the process of architectural design, he proposed new methodologies using the forces of nature and constant experimentation with analog models as part of the process of creation-experimentation, proof of this is that the Catalan architect didn't use arcs with geometries resulting from the circle (half a point, pointed, among others), instead he used arcs of non-circular form called parabolic or catenary, using the force of gravity. The catenaries were exposed by Robert Hooke towards the year 1670, who argued that "in the same way that the flexible thread hangs like this, but inverted, the rigid arch will be held." Later the German architect Frei Otto focused his work on a set of experiments and methodologies around the forms generated in nature in response to forces, such as gravity, surface tension and atmospheric pressure, the results of those experiments with qualities of self-formation and self-organization, these last ones present in nature in living and inert beings.

The experimental work of Gaudí and Otto have been the precedents of what is currently called form-finding, a methodology that uses physical forces of nature, for the generation and transformation of form, integrating analog and digital techniques determined by different restrictions. Patiño (2018) proposes the following definition: form-finding techniques are strategies based on rules and physical principles that promote principles of transformation, based on the relationship between form, material and structure, these rules are usually algorithms formed by an input, a controlled process of variables and an output or results. This idea can be seen in figure 1.

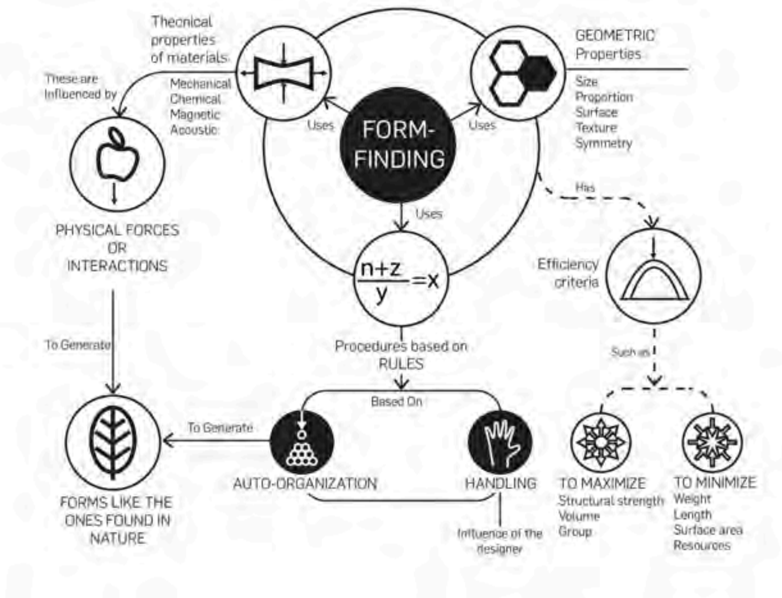
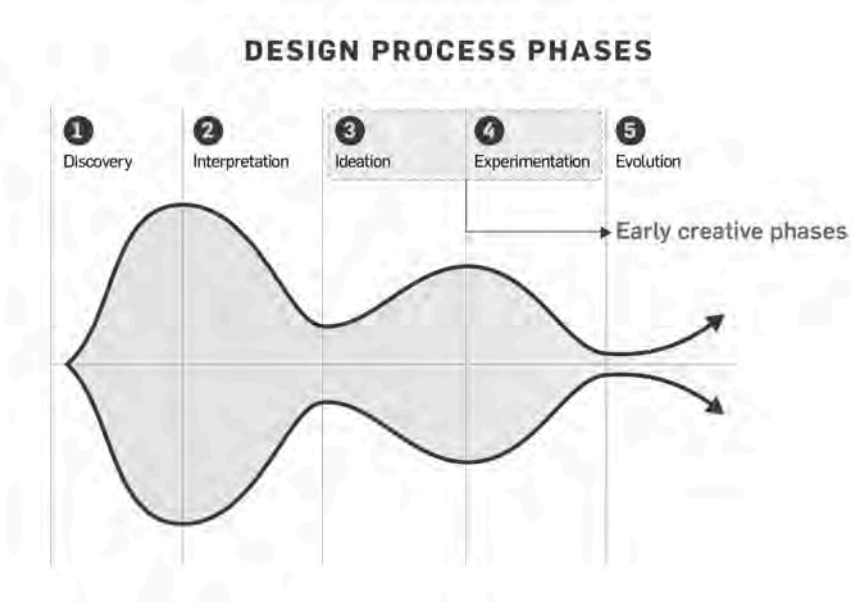


Figure 1
Form-finding schema, Patiño (2018).

Figure 2
Design process phases based on Design Thinking process for educators (IDEO & Riverdale, 2012). Drawing by Catalina Grellet De Los Reyes.



Form-finding techniques have been used mainly in architecture, in professional and academic areas, but the use of Form-finding techniques has been scarce and only occasional in industrial design, Nordin, Hopf & Motte (2011) mention that, compared to architecture, in industrial design there are few references of these methodologies and the experiences that have been done, but are not documented or published.

On the other hand, the early phases (ideation and experimentation) are important stages in the product design process, because each one concentrates a high level of creativity and it's the moment in which the form is generated. In this phases, a large part of the creative level of the design proposal emerges, because the designer's understanding of three-dimensional geometries intervenes in visual reasoning, in the cognitive level of concluding and inferring information based on visual data of the drawing or the model observed (Egenhofer, 2015). The creative process goes spontaneously from analytical to associative thinking (Gabora, 2010), agile and constant feedback loops are generated, so that the designer can generate a large number of internal representations in short periods and with a low cognitive effort. In figure 2 it's possible to see the design process phases, and early creative phases proposed by IDEO & Riverdale (2012).

As a result of the analyzed antecedents, the Research Line in Experimental Morphology (Morfolab) of the Industrial Design Faculty of the Universidad Pontificia Bolivariana proposes a research with the goal of developing a methodology to use analog and digital form-finding techniques to explore new research ideas, discovering new research possibilities about the identification of morphological characteristics with possibility of being used in design projects, especially in the early creative phases, in the context of formative research in industrial design program. This methodology as a result of the analysis, understanding, and systematization of the experiences and methods carried out by the research line during 20 years of experience in the Faculty of Industrial Design. The Research Line in Experimental Morphology has proposed different strategies to transfer the knowledge and experiences of the research projects to the industrial design students, this with the goal to build their research and design skills, propitiating an active and collaborative interaction with an empirical-experiential emphasis. The research line has done research projects in the field of morphology around four main themes: biomimetics, non-conventional structures, form-finding, materials and design. At the same time, cross-cutting themes are proposed: food design, digital fabrication technologies, parametric-associative and generative design.

This text shows the first results of the research project titled as Form-finding methodology as strategy for formative research in industrial design education, focused on developing a methodology to use analog and digital form-finding techniques in the context of formative research in industrial design, at Universidad Pontificia Bolivariana in Medellín, Colombia.

METHODS

Research project has been proposed with an empirical-analytical approach through action-research based method and using collaborative-participatory tools. The research proposal is based on the understanding of the phenomenon through direct participation in the experience, with emphasis on practical activities, in a dynamic interaction between professors-researchers and students of industrial design, also promoting an active learning process.

The figure 3 shows the stages of research project, the phases are the following: Identification of techniques, stages and variables, analysis and synthesis of information, methodological proposal, validation of the methodology, analysis and evaluation.

The research has been developed in different subjects of research in morphology in the Industrial Design program. Initially groups of students are organized, led by a multidisciplinary team of professors-researchers, who work collaboratively, first to define the type of experimentation, selecting the technique, the materials, processes and require-

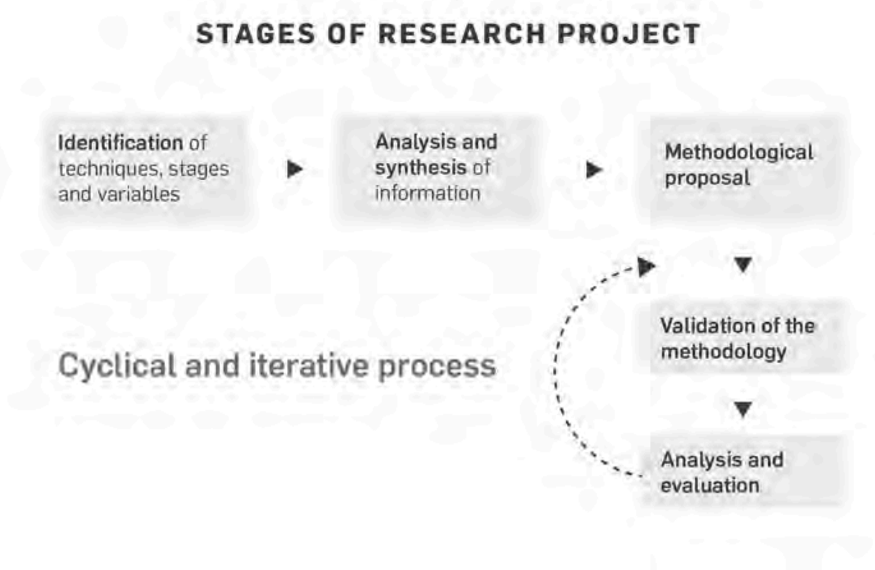
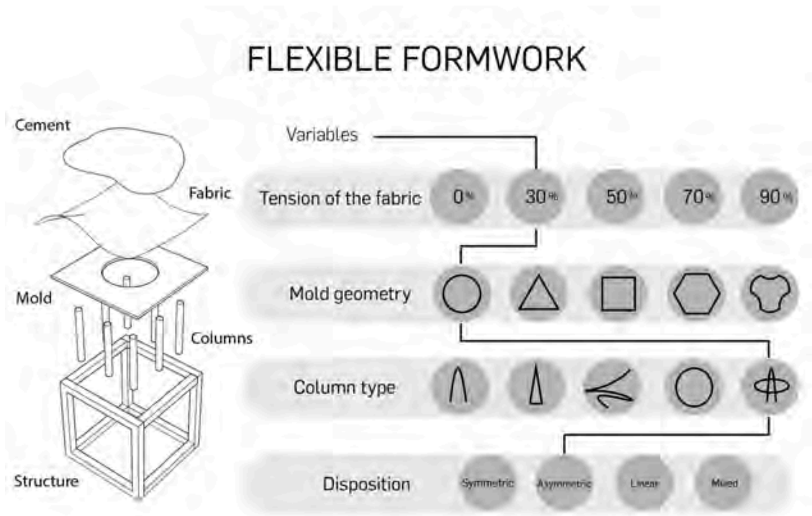


Figure 3
Stages of research projects, idea proposed by the authors. Graphic design by Catalina Grellet De Los Reyes.

Figure 4
Flexible formwork schema by Camila Aguirre, industrial design student.



ments involved, then the experimentation is carried out, with a photographic and written record of what happened. Finally, professors and students together analyze the results of the experimentation and synthesize the information obtained in order to identify stages, problems, variables and research opportunities that the technique showed. It's planned to analyze different cases to propose and improve continuously a methodology to be used systematically in formative research in the industrial design program.

RESULTS

Currently the research project is in the first stage, several case studies have been analyzed that have allowed an initial methodological approach. For this text we have selected highlighted cases, because their results have allowed to identify stages, variables, problems and key factors for the methodological approach, the selected cases are explained below.

Case 1: Flexible formwork technique (Iwamoto, 2013; Rojo, 2013; Swackhamer & Satterfield, 2013)

The goal was to generate solids with double positive curvatures through the use of elastic membranes and concrete, whose main property is to maximize the volume with the minimal surface. The sequential stages were to build the rigid structure, select the type of membrane in relation to its percentage of elongation or elasticity, put the molds and distribute the columns in the structure and deposit the concrete. The experimental variables were the membrane tension, mold geometry, column type, position of the columns. A Family of organic forms with potential to be used in facades and floors was obtained, however it's difficult to control the elasticity of the membrane, see figures 4 and 5.

Figure 5
Flexible formwork, photography by José Agudelo, industrial design student.

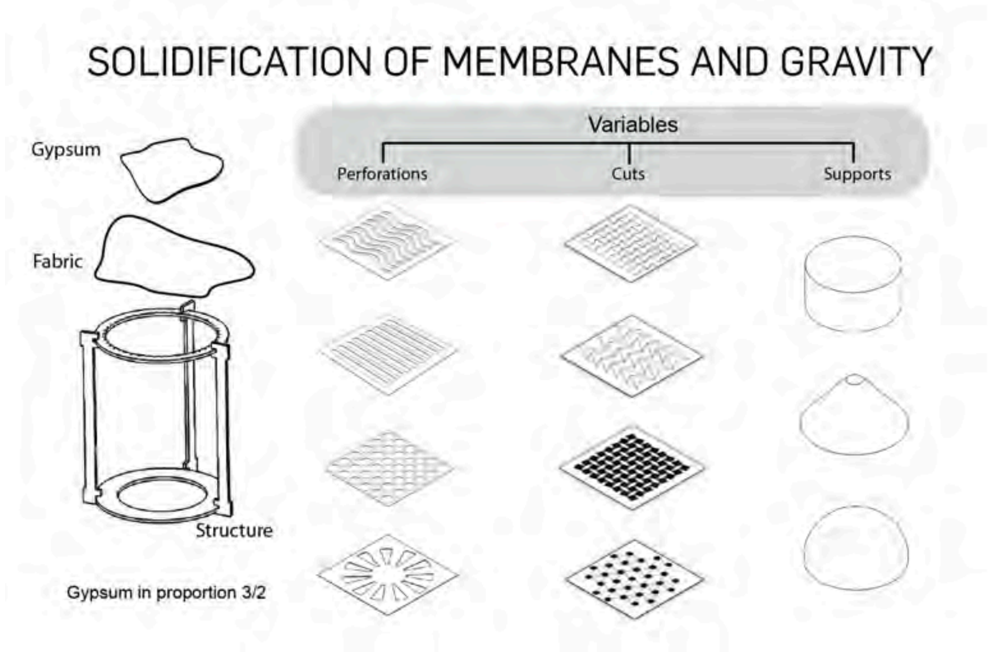


Figure 6
Solidification of membranes and gravity schema by Juliana Vélez, industrial design student.

Case 2: Solidification of membranes and gravity technique (Bletzinger, 2001; Jannasch, 2016; Dickson, 2003)

The goal was to find surfaces generated from catenary curves that when are solidified and inverted maximize their capacity to resist loads under compression. Firstly, the structure was built, the fabric was selected and cut, and the gypsum was prepared; then the fabric was immersed in the gypsum and these were hung on the structure. After the cast solidifies, the result is inverted and analyzed. It was observed that the cuts and perforations of the fabric are also influenced by gravity, which produces curvatures similar to the catenary. Although this kind of technique has been used frequently in architecture, in industrial design it hasn't been used; it's necessary to search applications where the resistance to compressive loads must be increased, see figures 6 and 7.

Figure 7
Solidification of membranes and gravity, photography by José Agudelo, industrial design student.

Figure 8
Flexible molds schema by José Agudelo, industrial design student.

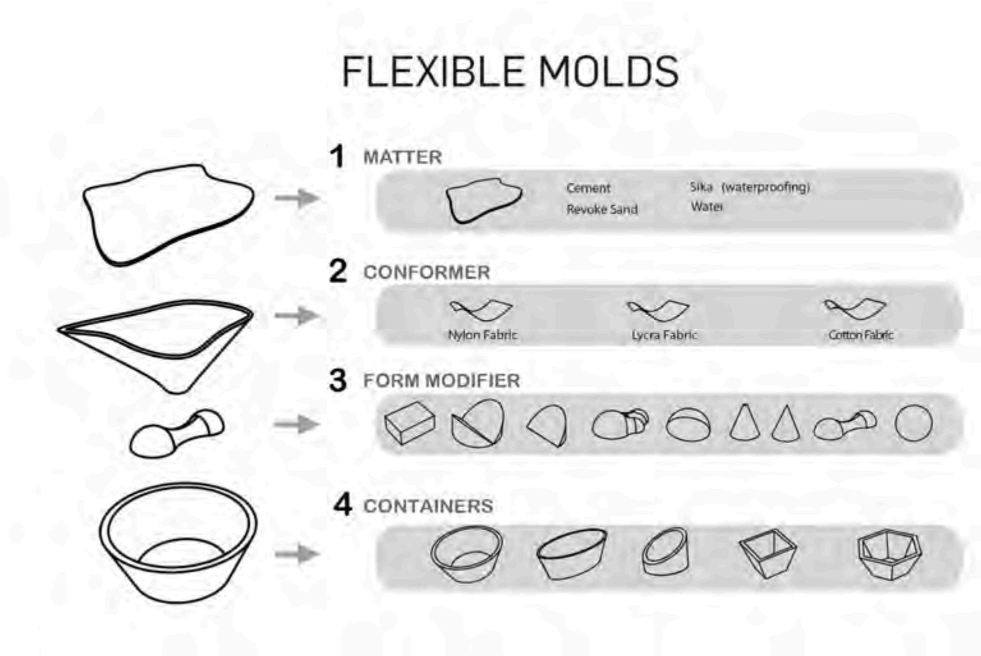


Figure 9
Flexible molds, photography by José Agudelo, industrial design student.

Case 3: Flexible molds technique (Manelius, 2012; Concretecanvas, 2015)

The goal was to generate concrete volumes with low cost molds, flexible and with irregular forms. The experimental stages were to prepare the containers, the form modifiers, the conformers (fabrics) and the concrete, the concrete must be prepared with low water content to ensure that it fits in the containers. The experimental variables were types of containers, modifiers and conformers (fabrics) that will influence the finish of the volume. It was observed that irregular volumes are generated as a result of the wrinkles originated from the interaction of the variables. The irregularity of the results makes it difficult to search for applications, see figures 8 and 9.

Methodological proposal

As a result of the analysis of different cases in the first stage of the research, a basic methodological proposal is made; the methodology has two goals, firstly it allows to systematize the perform and repetition of that kind of experimentation, secondly it's aimed to explore new research ideas about the identification of morphological characteristics with possibility of being used in design projects, especially in the early creative phases, in the context of formative research in industrial design. The figure 10 shows the sequential stages of the methodological proposal.

The methodology stages are the following: selection of technique, design of the experimentation, experimentation, analysis and discussion. The different stages and variables involved are explained below:

1. Selection of technique: firstly, it's necessary to select a technique and consequently to select a material and a physical principle, besides the technique can be analog, digital or mixed, such as: flexible formwork, solidification of membranes and gravity, flexible molds, inflated structures, minimal surfaces, tensegrity systems, catenary pottery, flexible wood, reciprocal structures, shells, bubbles, among others. The research line has been mainly worked with analog techniques, the use of digital techniques is just beginning to be proposed, through the use of the Rhino's plug-in named Grasshopper and Kangaroo to make physics simulations. It's important to emphasize that the experiences with analogical techniques allow to develop the basics for future digital applications.
2. Design of the experimentation: secondly, the experiment must be designed for professors-

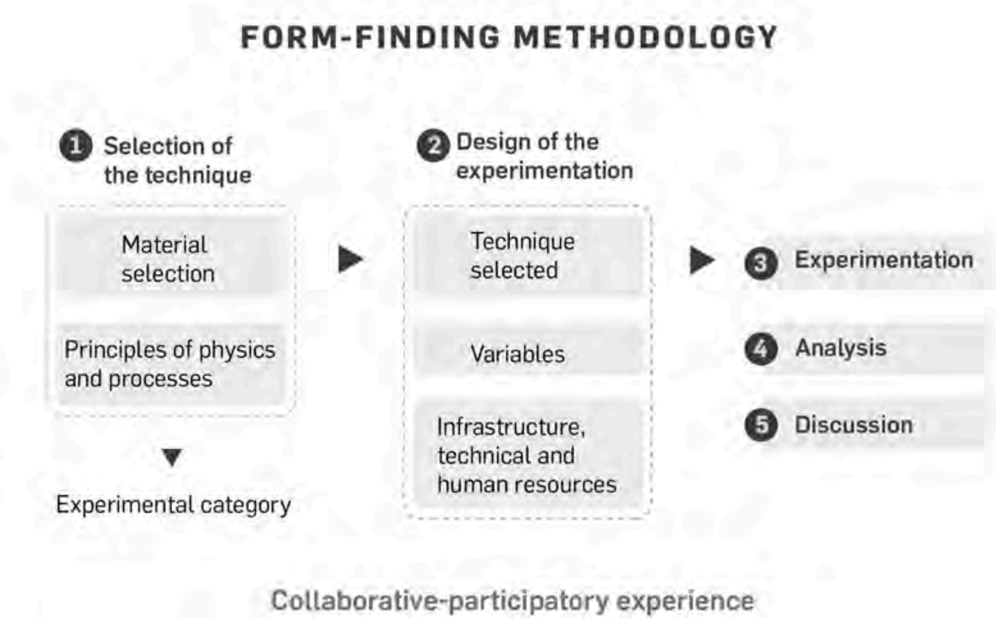


Figure 10
Form-finding methodology proposal, idea proposed by the authors. Graphic design by Catalina Grellet De Los Reyes.

researchers in collaboration with students, must be considered the selected technique, the variables, the infrastructure, technical and human resources.

3. Experimentation: this is the most important stage, the core and the main experience, in this stage students and professors-researchers carry out the processes of transformation of materials involved in the chosen techniques, in a collaborative-dynamic interaction in an active learning. In this stage, the photographic record is highly relevant and also a written record in the field diary, in order to identify different stages, variables, key factors, problems and opportunities; different formats have been developed to record the experimentation.
4. Analysis of results: the results are analyzed in order to identify stages, variables, and morphological characteristics or principles; It's also important to identify problems and unforeseen events. The analysis can be done through qualitative, quantitative and mixed methods.
5. Discussion phase: in the last phase professors and students discuss collaboratively about the experience and results. The results are analyzed to identify stages, variables and characteristics of this type of experimentation, as well as the problems and unpredictable situations. On the other hand, it's expected to find morphological principles with possibilities of being used in the first stages of the product design process, these analyzes open new possibilities of research in the industrial design program.

DISCUSSION

As a result of the first stage of research and lived experience, it's possible to outline the following ideas and conclusions:

The analysis of the case studies has allowed to identify different experimental categories, the stages, variables and key factors for the first methodological approach. In synthesis, the stages of the methodological proposal are selection of the technique, design of the experimentation, experimentation, analysis of results and discussion.

The methodological proposal aims firstly to systematize the perform and repetition of each kind of experimentation, secondly to explore new research ideas about the identification of morphological characteristics with possibility of being used in design projects, especially in the early creative phases, in the context of formative research in industrial design.

The research group have mainly used analog form-finding techniques and have just started to use digital techniques, however the experiences with analogical techniques allow to develop the basics for future digital applications; also analog techniques are important because they propitiate direct contact with materials and transformation processes, this can improve the ability of the students to understand. On the other hand, the use of digital techniques shouldn't exclude analog techniques, on the contrary, analog and digital techniques are complementary.

The methodology reveals a cyclic and iterative sequence, in which experience is the core of the process, the trial and error, doing and doing it again are important parts of the experimental process. It's expected to refine the proposal through the future analysis and experiences in a dynamic process with a collaborative-participatory interaction between professors-researchers and industrial design students in order to increase creative results. This methodological proposal will be part of the different formative research strategies at the Industrial Design program at Universidad Pontificia Bolivariana in Medellin, Colombia.

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Design Space Exploration of Initial Structural Design Alternatives via Artificial Neural Networks

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Increasing implementation of digital tools within a design process generates exponentially growing data in each phase, and inevitably, decision making within a design space with increasing complexity will be a great challenge for the designers in the future. Hence, this research aimed to seek potentials of captured data within a design space and solution space of a truss design problem for proposing an initial novel approach to augment capabilities of digital tools by artificial intelligence where designers are allowed to make a wise guess within the initial design space via performance feedbacks from the objective space. Initial structural design and modelling phase of a truss section was selected as a material of this study since decisions within this stage affect the whole process and performance of the end product. As a method, a generic framework was proposed that can help designers to understand the trade-offs between initial structural design alternatives to make informed decisions and optimizations during the initial stage. Finally, the proposed framework was presented in a case study, and future potentials of the research were discussed.

Keywords: *design space, objective space, structural design, artificial intelligence, machine learning, optimization*

INTRODUCTION

The conceptual structural design phase of an architectural project is a very critical stage since decisions made during that stage affects the whole process. Thus, it is very crucial for a designer to consider possible instances within the solution space so that the alternative selected by the designer would satisfy aimed objectives. Since conceptual structural design involves multi-objective criteria, it is impossible to process and analyze a vast amount of possible alternatives via the data-crunching capacity of a human brain. Therefore, this research aims to propose a novel approach in computer-aided analysis and design with the implementation of machine learning algorithms in which users can interact with the algorithm during the process of modeling and explore design space effectively by using the interactive computational methods.

Background

Background of this research has shown that the initial design phase is very important since the whole process is started to be defined in these stages. Therefore, it is crucial for designers to consider as much option and variable as possible to optimize the design process. Unfortunately, the data processing capacity of a human brain is limited to a portion of the enormous possibility of space; but processing data via machine learning can extend that portion and as a consequence, have a potential to augment the design space exploration process.

For instance, in a research conducted by Brown and Mueller (2017), a study was done on the design space catalog which is a collection of different options for designers to choose and how it can go beyond by designing with data. As a method, they reviewed the developments in four main categories that are interaction, automation, simplification, and visualization. Then they discussed that human-computer interaction should be integrated into early stage design and even in the initial brainstorming phase. Finally, they concluded that human-computer collaboration can harness the power of computational processes together with the creative capacities of designers to generate workflows that answer to the complexity of the architecture.

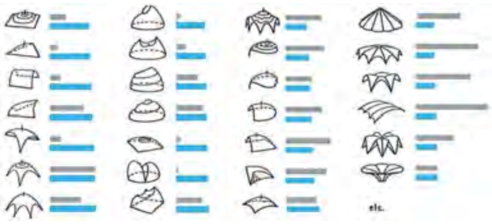


Figure 1
An example design space (Brown and Mueller, 2017)

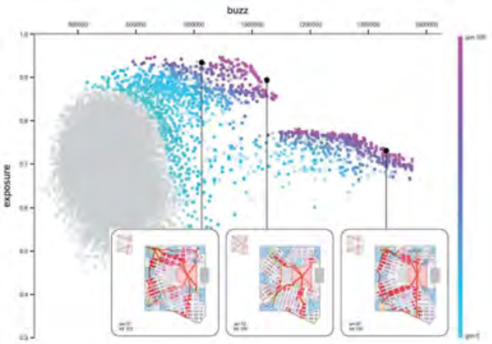


Figure 2
Quality metrics visualized within the solution space (Villaggi et al., 2017)

Also, in another research done by Villaggi et al. (2017), researchers proposed a novel design space approach to be used in generative space planning in architecture. The model they developed was based on a data structure that allows subdivision and merges operations on a floor plan controlled by a smaller set of input parameters. Also model includes evaluation for the performance of generated floor plans using a set of congestion metrics that allows them to be optimized by a genetic algorithm. Researchers also presented a set of guidelines and methods for analyzing and visualizing the quality of the model within the solution space (Figure 2). Finally, researchers concluded that the developed model could allow designers to break free of standard rules and explore a broader range of design possibilities.

Research Problem and Objective

The problem of this research was mainly based on the idea that the complexity of computer-aided analysis and design models are increasing exponentially and it is getting more complicated for a designer to consider numerous design alternatives within the design space. Besides, review on previous research showed that computational methods and machine learning algorithms have a potential to enhance the design space exploration as Alpaydin denoted this in his book as "Machine learning will help us make sense of an increasingly complex world. Already we are exposed to more data than what our sensors can cope with, or our brains can process." (2016).

The main objective of this research is implementing machine learning models into the computational design tools and allowing designers to harness the data processing capacity of computers to explore design space more effectively. Another objective is that since previous research within the field of computational design mainly focuses on optimization and search for 'the solution', this research aims to propose a framework which derives correlations between design space and objective space to allow the designer to explore multiple solutions by controlling aimed structural performance.

Figure 3
Different design alternatives generated by different parameters

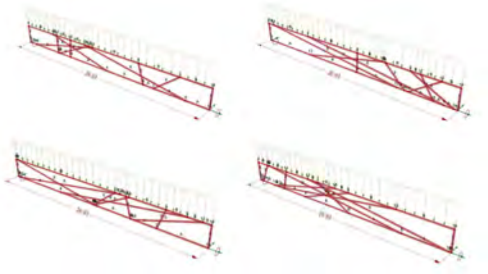
RESEARCH DESIGN

Since every design process is unique and aim of the research was not to search for the single optimum solution for a specific problem but to learn the solution space of a user-defined problem, the main research question was whether initial design alternatives proposed by the designer used as a starting point for the algorithm or not. Also, another research question was to test machine learning algorithms to see if they can extract features and derive correlations within multi-objective criteria to make an evaluation.

The hypothesis of this research was based on the idea that machine learning algorithms have the potential to be implemented to the initial structural design phase as a pier to enhance design space exploration. Secondly, since structural elements have measurable quantitative criteria, metrics for evaluating the performance of initial structural design alternatives can be used for multi-objective optimization of structural models. Last but not least, since structural elements have rule-based criteria, machine learning models have the potential to extract features and derive correlations in data to make accurate evaluations.

Material of the Research

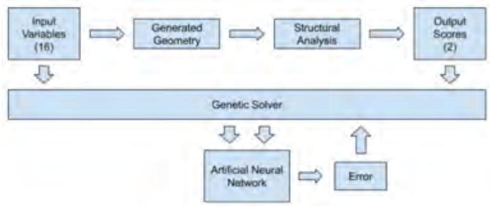
The first research material is the initial geometry data from the designer modelled within the conceptual structural design phase, which should have parameters to generate new design alternatives. For this research, Karamba's sample parametric structural design models were used (Preisinger, 2016). The second research material is the structural performance data composed of the total mass of the structure and maximum displacement, calculated with Karamba parametric engineering components (Preisinger and Heimrath, 2014). The last research material is artificial neural networks (ANN), which was fed with input data composed of design variables and output data comprising structural simulation data. In this study, Crow artificial neural network component developed by Felbrich (2016) was used.



Method of the Research

As a method, listed parameters that control the initial structural geometry were initialized within a gene pool to generate new geometries in a randomized and unbiased manner (Rutten, 2013). After creating new geometries by using Galapagos genetic solver (Rutten, 2010) that shuffles input variables, two sets of data that are maximum displacement and the total mass of structure were calculated with finite element method by Karamba components for each design alternatives. Since two sets of recorded quantitative data for maximum displacement and the total mass have different ranges (0.03 to 0.45 and 4175 to 9138 respectively), both were normalized and remapped between 0 to 1 just as input data in order each data feature to affect learning model equally. Then both input data from a gene pool that controls the geometry and output data from the simulation that gives the score for displacement and total mass were assigned to an artificial neural network engine to evaluate (Figure 4).

Figure 4
Flowchart of the research method



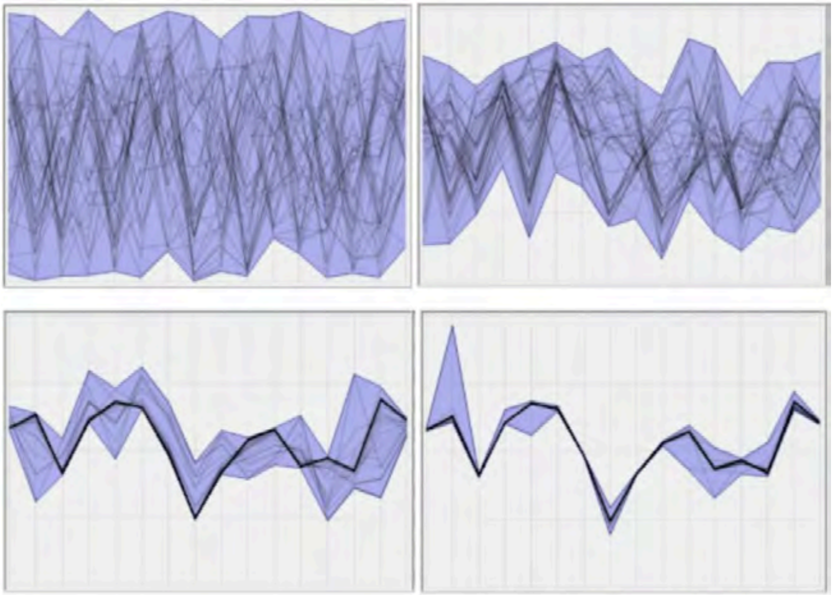


Figure 5
Area chart of 16 input variables which defines the design space for generations 1, 5, 25 and 50

Figure 6
Scatter plot of 2 output variables which defines the objective space: mass of the structure and maximum displacement

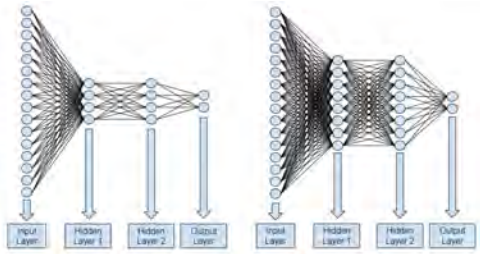


Figure 7
The network architecture of 4 by 4 ANN and 8 by 8 ANN for 16 inputs and 2 outputs

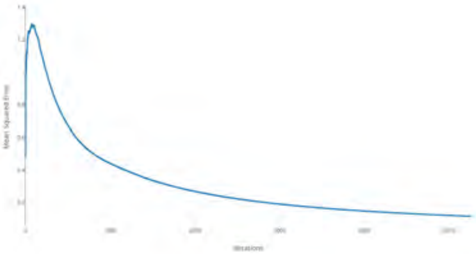


Figure 8
Line graph of mean squared error over iterations

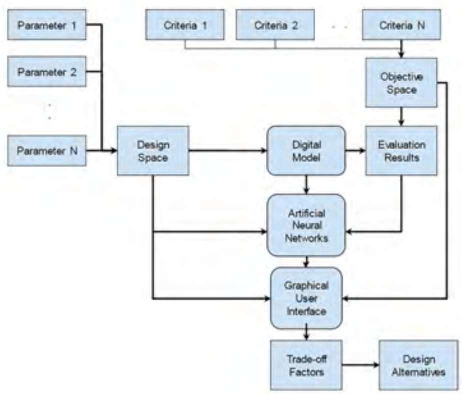


Figure 9
The extended generic framework proposed for future studies

ANALYSIS AND RESULTS

Sample parametric model for optimization of truss diagonals from Karamba was used for data capturing process, as mentioned in the material of research. This sample parametric model has 16 input variables (start and end point of 8 truss diagonals) that control the whole geometry and 2 selected output variables that are the mass of the structure and maximum displacement. Data collected by randomizing these 16 variables within a gene pool in a randomized manner by using Galapagos genetic solver and recording 2 output data for each design alternative. Finally, mean squared error of a trained artificial neural network was calculated with the formula below where N is the number of data points, f_i is the value returned by the model and y_i is the actual value for each data point i.

$$MSE = \frac{1}{N}\sum_{i=1}^{N}(f_i - y_i)^2 \qquad (1)$$

After data were collected, initial training of the artificial neural network was conducted with 350 and 1150 different design alternatives, and it was observed that the error of artificial neural network decreases as more data were given. After that, Galapagos evolutionary solver was used to generate different design alternatives by genetic shuffling and fed the artificial neural network with input and output in each iteration to minimize the mean squared error of the ANN. After 5264 iterations, mean squared error rate of the artificial neural network was decreased to 0.11614 when ANN with four by four hidden layer architecture was used. After that, the same data of 5264 different design alternatives were given to an ANN with eight by eight hidden layers and mean squared error was decreased to 0.063562. Finally, the trained artificial neural network with the mean squared error rate of 0.0636 was used to predict diagonal support positions of a truss when different scores for mass and displacement were given, and it was observed that predicted positions were accurate.

CONCLUSION AND FUTURE PROJECTIONS

To conclude, this research has shown that machine learning algorithms have the potential to be implemented to the initial structural design phase to catalyze design space exploration. Also, the mean squared error rate has proven that machine learning algorithms can be trained to extract features and derive correlations within multi-objective criteria to make accurate and precise predictions. Yet, this research must be extended by implementing the same methodology to different design examples to prove the hypothesis that the proposed learning model is sufficient to learn the solution space of various problems. Also, the study should be implemented with more variables within the design space such as material type, thickness, number of supporting elements, load type and quantity and so on to test if the learning model can still learn the design space by using correlations between inputs and outputs. Therefore, a generic framework is proposed for future studies (Figure 9), based on the initial study conducted within the scope of this research.

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Tool for evolutionary aided architectural design. Hybrid Evolutionary Algorithm applied to Multi-Objective Automated Floor Plan Generation

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The paper presents the ELISi multi-criteria optimisation application for AFPG based on Hybrid Evolutionary Algorithm (HEA). The research aims to create functional computational design tool for architects, mimicking the workflow of architectural design process. The article includes explanation of the proposed approach: problem representation, genetic algorithm operators, fitness functions definitions, post processing operations, software functionalities and workflow as well as achieved architectural results and outline of future research.

Keywords: *MOO in CAAD, automated floor plan generation, HEA*

INTRODUCTION

The computational design significantly improves design processes, liberating the human mind from carrying out complex calculations, making the whole process much faster and more effective. The recent technological breakthroughs have the potential to vastly broaden functionalities of architectural software, which today are vital in the architectural design optimization, both geometrically and qualitatively. Authors intent to achieve this goal by creating a computational tool assisting architectural design process.

Automated Floor Plan Generation (AFPG) tools development is one of the contemporary directions of the computational tools solving architectural problems advancement. Thought present in the architectural research from the early days of computer era (Mitchell, 1970; Mitchell and Dillon, 1972; Weinzapfel and Negroponte, 1976) it still is not fully resolved problem nor no fully developed design software using AFPG has yet been created. It allows to effectively search spaces of measurable design conditions leaving architects area for making the most important design decisions. In recent years, this area is experiencing dynamic growth as exemplified by promising academic research, eg. (Merrell, Schkufza and Koltun, 2010; Willis, Hemsath and Hardy, 2012; Liu et al., 2013) and [1].

Authors assume that automation of the search process for the optimum floor layouts concepts broadens the spectrum of the design solutions that meet the design requirements and accelerates the architectural design process. Additionally, the designer's creativity is supported by new non-obvious solutions of better quality by multi-criteria optimization.

Problem outline. The paper presents the application for AFPG with the use of multi-criteria optimisation based on HEA (Myszkowski et al., 2018; Laszczyk and Myszkowski, 2019) (based on Non-Sorting Genetic Algorithm - NSGA-II (Deb et al., 2002) and Greedy-based algorithm) to produce the optimal floor plan solutions based on multiple architectural criteria:

rooms connectivity, preferred area, width and length, proportions and their location relative to world sides. The article presents the main functionalities, tool workflow and achieved architectural results.

Project aims. The developed software was based on previously conducted research - see (Nisztuk and Myszkowski, 2019) and the survey (Nisztuk and Myszkowski, 2017) conducted on the professional architects - which clarified the set of expected features and functionalities that the proposed application should fulfill. The main goal includes the following features: an intuitive, interactive and fast program, suggesting optimum ideas rather than generating ready-to-use solutions, where the user has full control over the computational design process. The use of the software should proceed deductively, resembling stages of architectural design.

THE SOFTWARE OVERVIEW

This article describes a new application ELISi (EvoLutionary ArchItectural Aided DeSign) (Nisztuk and Myszkowski, 2019) supporting the conceptual stage of designing architectural floor plans via AFPG. During the development of the presented software, the main emphasis was put on its usability and intuitive functionality for the target audience - the architects. To achieve that, the authors assumed the tool workflow should be based on the stages of the architectural design process, especially during the initial step of the design data input. Such workflow was specially recreated in the initial part of the input design data process. The user is guided through the design process by an intuitive *wizard-like* graphic interface. To suggest relevant design results, the software uses real architectural design conditions (general architectural design guidelines and legal requirements) as the AFPG constraints solved and optimised by NSGA-II. The constraints are collected in the set, called *Design Canons*. As such the presented software is part of the growing user-centred trend in the contemporary development of architectural software. Other examples can be found in, eg. (Rodrigues et al., 2015; Nagy et al., 2017). Authors also believe that the software can assist the designer creativity by suggesting useful design solutions being the outcome of AFPG.

The software is focused on aiding the conceptual stage of the floor plan design process, therefore the floor plan representation is simplified to rectilinear form, reducing other architectural details, which corresponds to an architectural practice routine. ELISi in presented version focuses on single-family housing due to its relatively high complexity of functional programs especially in regards to a high number of different room categories and their functional connections. Currently, the software consist of 27 definitions of different room types and can be easily expanded.

Development environment. The software Graphical User Interface (GUI) was developed in the Unity 2017 game engine. The selected environment offers important features such as the possibility of software deployment to multiple platforms (PC, Mac, Web, Android and more), C# language, powerful 3D engine and rich environment of premade assets and libraries (via NuGet package manager for .NET) which greatly facilitate the development process.

The ELISi application in a current stage is the desktop application dedicated for PC/Windows platform. However, authors plan to develop the client-server version for the testing purposes. The WebGL build options allow to publish Unity developed software as JavaScript programs and to run it in a web browser. Finally, Unity is useful in designing and developing interactive GUIs.

The ELISi is ready for deployment on various platforms but currently does not have direct integration with existing architectural design software. Further development will be focused on the creation of Grasshopper plug-in which will allow the direct integration with leading architectural Building Information Modeling (BIM) software.

The software structure. The ELISi structure is schematically presented on Figure 1. The work starts with the input of design data (expected number of rooms, their type, preferred area, location relative to world sides) via the *wizard-like* interface. The rooms topological connectivity is defined via the Force-directed graph. Subsequently, the preferences are confronted with information from *Design Canons*. If any preference excess the already defined limits or violates the architectural design rules, the corresponding value is copied from *Design Canons* set. Next, the application presents a set of architectural layouts meeting design requirements. Each layout represents a solution that is a unique trade-off of design requirements. Then, the floor plan 2D representation is presented with its relevant design data (see Figure 3). The floor plan can be previewed as the isometric conceptual 3D model - internal and external walls with the architectural openings (see Figure 4). In addition, the user can preview solution from Pareto Front on the 3D scatter plot (see Figure 2).

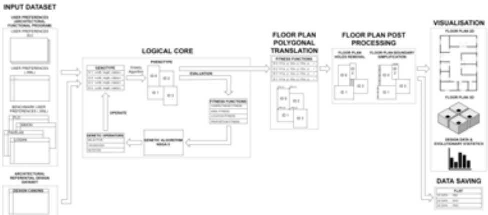

Figure 1
General schema of ELISi workflow. Based on (Nisztuk and Myszkowski, 2019).

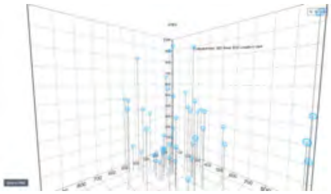

Figure 2
3D Scatter Plot preview of solutions from Pareto Front (the floor plan variations with non-dominated fitness functions values) created by ELISi.

The ELISi workflow is presented online [2].

The software logic

The logical core of the application is based on the Evolutionary Algorithm. It is a metaheuristic inspired by natural evolution. It codes solution of the problem in genes, uses solution selection in the population (to give pressure for better solutions), applies mutation (to change single gene value) and crossover (to link two solutions). Such operators implement evolution in fitness function environment to build a better and better solution. In ELISi application HEA for multiobjective optimisation based on hybrid NSGA-II and Greedy-based algorithm has been used. Greedy-based algorithm constitutes the mechanics of floors plan generation while modified multi-criteria NSGA-II algorithm provides the searching procedures for feasible floor plan solutions. The evolutionary selection process is based on four implemented fitness functions being the representation of requested design criteria - (1) the floor layout compactness (*ComptactnessFitness*), (2) the room preferred area (*PreferedAreaFitness*), (3) the room preferred location relative to world sides (*PreferedLocationFitness*) and (4) the room proportions (*ProportionsFitness*). Room topological connectivity is always correct because it is enforced by the Greedy-based algorithm. Also to improve quality of floor plans, two post-processing procedures have been implemented: adjustment of layout boundary irregularities and filling the *holes* inside the layout boundary.

The solution model. The ELISi (Nisztuk and Myszkowski, 2019) solution space is defined as follows: arrange (locate in 2D space) all rooms (described by user preferences) and define their size to optimize their organisation according to multiple fitness functions (minimization problem) and meeting the assumed user design preferences and design constraints (*Design Canons*). The ELISi solution is described by Evolutionary Algorithm as *floorPlan* - a sequence of rectangular rooms (r_i) described by their width (w_i), length (l_i) and position (x_i, y_i) in layout as $r_i(x_i, y_i, w_i, l_i)$.

After defining the preferred localisation and measure for each room, the final solution should be build to get the floor plan by the Greedy Algorithm.

Greedy algorithm (Greedy() procedure). The Greedy algorithm creates solutions (floor plans) which are *feasible* (topologically correct). The proposed algorithm (see pseudo code bellow) creates the floor plan using the list of dimensions scale factors (defined for all rooms separately) and sequence of rooms ordering. The algorithm scales rooms and assigns the first room position to the floor plan centre. The *SCALE* (room width and length scaling factors, defined separately for each room) operations scale rooms within limits of constraints defined by *Design Canons* set. Next, the first room in *SEQ* (rooms ordering sequence) is placed, followed by its neighbours (rooms topologically connected in user preferences). Placed rooms are removed from *SEQ* list. *PlaceRooms* places the rooms in the position (*X*, *Y*).

```
procedure Greedy (SCALE[N], SEQ[N])
for room ← 1; N do
 Flat[room].width*=SCALE[room].width
 Flat[room].length*=SCALE[room].length
end for
X ← Flat.Width/2
Y ← Flat.Length/2
while |SEQ|1 do
 CurrentRoom ← SEQ[0]
 PlaceRooms(Flat,CurrentRoom,(X,Y))
 Neighbors ← CurrentRoom.getNeigh(SEQ)
 PlaceRooms(Flat,Neighbors,(X,Y))
 SEQ:=SEQ\( CurrentRoomNeighbors)
end while
returns floorPlan(Flat)
```

Hybrid Evolutionary Algorithm (HEA() procedure). Previously defined AFPG problem is based on single-criteria function (Nisztuk and Myszkowski, 2019), but to get a solution, multi-objective HEA should be redefined. The classic NSGA-II (see pseudo code below) has been used. NSGA-II finds the optimal sets of *SCALE* and *SEQ* (the Greedy-based algorithm input). The illustration (see Figure 1) presents the ELISi structure and data flow. The process begins with the input of user preferences defined as constraints. The preferences include information on rooms number, categories, preferred areas and their location. If any preference is not provided by the user, its value is copied from *Design Canons*. Next, the HEA *genotypes* are initialised randomly. In the next stage, Greedy-based algorithm is executed to transform *genotypes* into floor plans (*phenotypes*) which are then evaluated by fitness functions. Next, evaluated floor plans are selected, modified by genetic operators (mutation and crossover) to create the next generation. Finally set of "the best" individuals are selected as the Pareto front and presented to the user as the 2D/3D floor plans.

The ELISi *genotype* is described by the sequence of rooms (*SEQ*[*n*]), rooms scaling factors (*SCALE*[*n*]) and additional room transformation matrix (*T*[*n*]) defining if the given room should be rotated. The ELISi uses three types of mutations: room sequence swap of room sequence, Gaussian modification of room scaling factor and random change of room rotation values (*true*, *false*). The swap operator changes the order of two randomly selected rooms. The second operator allows small changes in room scale. The last mutation improves the evolution process by introducing additional diversity. The crossover *SX* operator (Single-Point Crossover) produces two offsprings by swapping parts of two chromosomes of parents chosen by the tournament selection.

```
procedure HEA ()
pop := CreateNewPopulation()
Greedy (population)
CalculateAllFitnesses (population)
for index ← 0; Generations do
 parents:=selection()
 offspring:=crossover(parents)
 offspring:=mutation(offspring)
 Greedy(offspring)
 CalculateAllFitnesses(offspring)
 prntChild ← MergePop(pop,offspring)
 arrangedPop ← NonDominSort(prntChild)
 pop ← ChooseBestIndiv(arrangedPop)
 paretoFront ← GetParetoFront()
 EvaluateParetoFront(paretoFront)
 CurrentGeneration++
end for
SaveBestIndividuals()
returns pop
```

Fitness functions

The ELISi solution is solved by HEA as *floorPlan* - a sequence of rectangular rooms (r_i) described by their width (w_i), length (l_i) and position (x_i, y_i). Each *floorPlan* is evaluated by the four fitness functions describing its design properties. Their values are assigned as scores to each *floorPlan*. Based on their values all *floorPlan* are ranked during each generation and the best ones are allowed to pass their genes to the next iteration. After determining the value of each fitness function, its value is normalised to the domain <0...1000>. Their values are minimised which means the best value is 0.

Floor plan compactness fitness function (see formula 1 and 2). The function *ComptactnessFitness* evaluates the floor plan compactness by determining its bounding box area B and reducing its value by the summed area of all rooms. If the value equals 0, the rooms cumulative surface covers the floor plan bounding box meaning there is no lost space and the floor plan is the optimal one.

Room area fitness function (see formula 3). The function evaluates the area of each room based on the value of preferred area A_i provided by the client for a given room, during the design data input. The value of preferred area A_i is reduced by the current area of the room determined by its length l_i and width w_i and summed with the values of other rooms to *PreferedAreaFitness*. The l_i and w_i have a domain originating from *Design Canons*, assigned based on the type of current room.

Room preferred location fitness function (see formula 4). The function evaluates the location of rooms in relation to four world sides (*North*, *East*, *South*, *West*). First, the location of all rooms is translated to list of edge indexes determining which edge of room rectangle should be outer. World sides have the edge indexes assigned as follows: *North* - 1, *East* -2, *South* - 3, *West* - 4. Next, the value of the ED_i counter is specified for each room, by the number of requested indexes of outer edges. Then each room edge is checked for being outer. If the current edge is outer one and its index matches the index of requested edge, the value of ed_i counter is increased by one, starting from 0. Finally, the value of ED_i is reduced by ed_i and summed with the values of other rooms to *PreferedLocationFitness*. A given room is properly located if $ED_i - ed_i$ equals to 0.

Room proportions fitness function (see formula 5). This evaluation function measures the *length-to-width* ratio of each room. Currently, the authors proposed 5:3 ratio of all room types, which is consistent with the architectural practice. In the future versions of the ELISi tool, each room type should have its own ratio, specified in the *Design Canons* set. For each room selected, golden ratio value is reduced by current room w_i to l_i ratio. Then the results absolute values are summed to *ProportionsFitness* value.

$$B = \left(\max_{i=1}^{n}(x_i + w_i) - \min_{i=1}^{n} x_i\right) \cdot \left(\max_{i=1}^{n}(y_i + l_i) - \min_{i=1}^{n} y_i\right) \tag{1}$$

$$\text{CompactnessFitness} = B - \sum_{i=1}^{n}(w_i \cdot l_i) \tag{2}$$

$$\text{PreferedAreaFitness} = \sum_{i=1}^{n}|A_i - (w_i \cdot l_i)| \tag{3}$$

$$\text{PreferedLocationFitness} = \sum_{i=1}^{n}(ED_i - ed_i) \tag{4}$$

$$\text{ProportionsFitness} = \sum_{i=1}^{n}\left|\frac{5}{3} - \frac{w_i}{l_i}\right| \tag{5}$$

- i - current room number; n - total number of rooms; w_i - current room width; l_i - current room length; x_i - current room centre X-axis position; y_i - current room centre Y-axis position; A_i - current room prefered area; ed_i - current room number of outer edges matching preferred outer edges; ED_i - current room preferred outer edges number.
- For ProportionsFitness: if l_i>w_i then w_i=l_i; l_i - current room length. If l_i>wi then l_i=w_i.

Graphical User Interface

The already conducted research (Nisztuk and Myszkowski, 2017) helped the authors to define a set of requested by the target user group (the architects) functionalities and features of the AFPG software. The software should be an interactive and intuitive tool complementing the user design experience by suggesting optimal ideas rather than creating final solutions, giving the user (if requested) the full control over the computational process. The workflow should be similar to the stages of the typical architectural design process.

Figure 3
The main ELISi screen presenting the 2D floor plan representation, information about design properties of requested functional program and data of the evolution process (fitness scores). The left table includes the user design requirements, the right table presents the design data of the resulting floor plan created by ELISi. The line diagram presents the best, the worst and the average scores achieved during the generation process while the Radar diagram visualises scores of the selected floor plan achieved for each design criterion.

Wizard-like interface. To achieve the required features of intuitiveness and usability, one of the main design goals during the creation of software was to design and implement the GUI which will be simple and easily understood by the user. The GUI makes possible to implement a *wizard-like* design which guides the user through the steps of the design process resembling the architectural design stages. It begins with gathering of all requested design properties. With the series of screens, the user enters data on the number of rooms, their areas, types, locations and establishes main functional relationships.

When the user inserts all required design data, the software begins the floor plans generation process. The architecture plans are generated, modified and evaluated in iterations by Evolutionary Algorithms. When this process is finished, on the main screen (see Figure 3) ELISi presents a set of floor plans meeting the design requirements, accompanied by information on their design properties. First, ELISi presents the most suitable solution - the floor plan which achieved the lowest sum of scores for each design criterion visualized on the Radar diagram. The better the score the closer to the centre the corresponding part of the diagram is. The line chart presents the overall floor plans scores behaviour during the generation process.

2D floor plan representation (see Figure 3) includes information on room geometry and its type identified by the category colour. In addition, the location of doors and windows is present. Each floor plan can be previewed as the isometric conceptual 3D model. The 3D result screen presents the isometric view (see Figure 4) of the selected layout as internal and external walls with the architectural openings. Generated solutions can be previewed by moving the slider button. Each layout represents a solution that is a different trade-off of design requirements. For the population scores preview, the 3D scatter plot option is present (see Figure 2).

2D Force-directed graph as a topological connectivity representation tool. To facilitate the process of establishing the topological connectivity between rooms, the authors used interactive 2D Force-directed graph (see Figure 5). The Force-directed graphs being a simple physic simulation (Kobourov, 2012) allow creating graphs drawings in an aesthetically pleasing and attractive way. Each room is represented as a circle being at the same time the graph node. The circles can be connected to each other creating the graph edge, at the same time establishing the desired room topological connectivity. Each circle can be edited by changing its category and area. Each node is the centre of repulsion force acting on the nodes around, each edge acts as a spring attracting connected circles to each other. After connecting nodes, the graph tries to find the equilibrium between attracting and repulsing forces.

To feature additional spatial relations between rooms, the visualisation of zoning connectivity has been added (see Figure 5). Each room type can be included in one of four functional zone category representing types of function in floor plans: day zone, night zone, utility zone and communication. The preview is realised with the use of 2D implementation of Metaballs (Blinn, 1982). Each graph node is the centre of metaball. The nodes from the same functional category create the metaballs which can join together creating an organic form of zone category preview.

Figure 4
Example of the 3D preview of the floor plan created by ELISi.

Figure 5
The Force-directed graph representation of the architectural functional program and rooms topological relations. Each room type represented as graph node is assigned to one of floor plan functional zones: Day zone (yellow), Night zone (blue), Utility zone (violet), Communication (grey).

Design Canons - the architectural design set

The architectural design set contains the guidelines and principles based on the widely accepted architectural practice and ergonomic research (Neufert and Neufert, 2012). Being the referential "rule book", the set is the source of design information inside the ELISi application. Design information is presented in the matrix form defined for each room type. The matrix includes information on topological relations, dimensions, areas, preferred floor, room proportions, locations regarding the world sides and area tendency. The area tendency determines room area behaviour during the generation process (the maximization, the minimization and neutral).

The information from the user input needs to be limited to allowed design requirements. If information is outside the allowed values, the user is informed by the software and the nearest allowed value will be proposed. On top of that, the authors propose additional requirements, like legal design constraining the general universal guidelines with the local legal regulations. In the current ELISi implementation, the Polish construction law is used.

Post Processing of floor layouts

To further improve the quality of the floor plans, two post-processing algorithms were proposed. The post processing mechanics assume shifting the position of room edges, because of that a new way of floor plans representation was necessary. The *flatPolygon* translating *floorPlan* rectangular rooms description and storing its data in the form of their polygons (vertices and edges) was created. It contains polygonal description of the layout boundary and list of rooms with information on their polygons, category, neighbourhood and area.

Removing holes from the floor plan. During the initial generation stage, the rooms are described as rectangles which can introduce the empty spaces (*holes*) between them. The removal of *holes* is done by adding their surface to adjacent rooms (see example on Figure 6). The *hole* can take the shape of an orthogonal polygon with an even number of sides, greater than or equal to 4 - the simplest form is a rectangle. In case of a higher degree of complexity (Ueckerdt, 2011), there is a need to divide such polygons into basic constituent shapes - rectangles. To obtain optimal rectilinear decomposition of polygons, the authors used an algorithm based on bipartite matching algorithm (Suk, Höschl and Flusser, 2012) based on the [3] implementation. The algorithm returns a list of rectangles that decompose surface of a polygon to the smallest number of non-overlapping rectangles. After simplification of *hole* shapes, the rectangle surfaces are assigned to adjacent rooms.

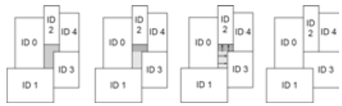

Figure 6
Stages of floor plan holes removing during the post processing stage of ELISi software.

Simplification of the layout boundary. The second type of post processing operation is designed to reduce the complexity of the floor outline making it more regular and takes place at the user's request (see an example on Figure 7). The algorithm focus on combining the neighbouring, parallel edges of the layout boundary polygon.

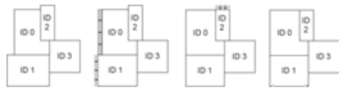

Figure 7
Stages of floor plan boundary simplification during the post processing stage of ELISi software.

EXPERIMENTATION RESULTS

To verify the ELISi application the authors prepared five benchmark cases of real-world architectural functional programs and their rectilinear representations (Nisztuk and Myszkowski, 2019). The collection contains three contemporary programs of single-family houses, one example of a classical modernist architectural layout with the extensive functional program and one example of a vernacular program of a house located in Rio de Janeiro's dense urban favelas area [4]. They were used to validate the performance of the selected methodology based on its ability to recreate the original floor plans.

ELISi results on benchmark floor plans. The authors selected 12 sample results achieved with the current version of ELISi (see Figure 8). The floor plans were created based on benchmark functional programs, with the post processing mechanics applied. Floor plans contain information on windows and doors location. ELISi system created functional architectural floor plans with rooms of good proportions and with clear zonal separation. The current version of ELISi takes into account the ground floor of the functional programs.

One can be concerned that the current floor plan description is too simple - it is based on the rectangular room outlines and simple location of architectural openings. The authors focus on the conceptual design stage, where the typical architectural designs are presented in the form of rectangular diagrams.

Figure 8
The example floor plans generated by ELISi software, with post processing algorithms applied. Each room is distinguished by its category colour and name.

FUTURE WORKS

Current ELISi version is the Work In Progress (WIP) and is in the process of development. This section contains information about features already in the process of implementation ((1) and (2)), new optimisation criteria and additional features planned to be developed (3), as well as more far-reaching plans for application development (4).

Floor plan edge shifting optimization (1). After the first stage of floor plan generation (the arrangement of rectangular rooms in relation to the world sides and application of the postprocessing mechanics, described in sections "The software logic" and "Post Processing of floor layouts"), the authors propose the second stage of detailed optimization of floor plans based on Evolutionary Algorithm. The procedure starts from selection for each room a random edge which is then moved in a perpendicular direction. The offset is stepwise taking values being the multiplication of the basic modulus (eg. the module of European drawing construction grid). The edge shifts are shared by adjacent rooms. Then, after moving the edge, a new wall segment is created, common for both rooms. This system allows to increase the regularity of floor plan walls and further improve geometrical quality of rooms.

Room editor with real-time optimization (2). The final stage of the floor plan creation proposed by authors is the manual edition of the room's edges by the user. The user has the ability to select any edge of the floor plan and move it in a perpendicular direction by stepwise offset taking values from the multiplication of the basic modulus. The shift triggers the single-criterion Evolutionary Algorithm optimisation of rooms whose geometry is altered by the edge shift. The optimization mechanics focus on the rooms geometry and area while changes are visible in real-time on the floor layout 2D preview.

Features planned to be developed (3). The authors prepared a list of new optimisation criteria and features planned for implementation, greatly improving the ELISi software workflow: introduction of other building typologies; checking if the given floor plan fits in the maximum allowed polygon on the plot area; multi-floor buildings; evaluation and optimization of the escape route lengths (evaluation of maximal allowed distance from a given room to the main building entrance - useful when developing floor plans of buildings with higher complexity); evaluation and optimisation of fire protection zones areas (floor plan organization according to the fire protection zones and evaluation of the zones areas based on the fire protection law - useful when developing floor plans of buildings with higher complexity).

Long-term development plans (4). In the long run, the application will be integrated with the Rhinoceros and Grasshopper software, which is one of the most popular platforms for computational design in Architecture. This will allow to reach a wide range of users and connect directly to one of the leading BIM software (Graphisoft Archicad). The authors chose to collaborate with this environment through own professional experience, but do not exclude integration with other platforms such as Autodesk Dynamo. Further improvement can include: full data about the 2D and 3D urban context (terrain, buildings, trees, etc), optimization criteria based on computational simulations (energy, circulation within the floor plan, other). Other further development directions will be defined on the basis of planned detailed surveys of architects regarding expected software functionality as well as ELISi tests carried out on the target users.

The Unity is based on C#, which is also the typical development language of Grasshopper plugins. Grasshopper being one of the main platforms for the *parametric design* in architecture is a natural field of further development for this type of tools. In addition, the Archicad software have an officially supported connection with this platform. While authors do not have the previous experience with the Dynamo environment, the integration of the existing tool to this platform seems to be a logical step.

DISCUSSION AND CONCLUSION

The ELISi is still in the development process, currently being the *proof-of-concept*. Because of that the constraints currently applied covers the traditional areas of the architectural optimization (room area, location, topological connectivity, etc). Such optimisation objectives are the foundation of architectural design, and when they will be fully developed, the additional optimization factors will be included in the ELISi. In ELISi development, creation of effective mechanics of floor plan generation and optimisation methods is as important as the creation of fully functional workflow (intuitive GUI) and coherent architectural methodologies (*Design Canons*).

The selection of single-family housing as case studies for the development purposes was dictated by several reasons. Focusing on one category of architectural objects allowed faster time of development. It is possible to create additional design sets (used as constraints for Evolutionary Algorithms) for other categories of architectural objects but it requires additional time. Furthermore, single-family house has low functional complexity (despite high number of possible room categories) understood as the number of rooms and their mutual relations. The relatively low number of rooms, typically ranging from ten to twenty allows to rapidly generate floor plans and check their architectural integrity.

The authors already conducted first promising results of ELISi capabilities to work with more complex functional programs of other building typologies: office building (32 rooms), conference centre (62 rooms) and multifamily housing (41 rooms). The functional programs were extracted from existing architectural designs. Programs had to be pre-processed to be compatible with the ELISi program. Although capable of working with complex programs, the ELISi produced floor plans of relatively poor quality. Based on the conducted research, initial conclusions for such behaviour points to lack of specific design constraints and optimisation objectives dedicated to various building typologies and lack of the *Design Canons* set adaptation to handle other types of buildings than single-family housing.

The current version of the software can be perceived as a transition version between the prototype and the advanced technology demonstrator. It can be especially seen in the evolution of ELISi logical core mechanics. The initial concept (Nisztuk and Myszkowski, 2019) and its extension (section

“The software logic”) was based on single-stage optimisation with the Greedy-based algorithm locating the rectangular rooms and the NSGA-II selecting the most suitable examples. Currently, the software mechanics evolve towards tree-stage optimisation process: (1) being the primal idea, (2) being the optimisation of the floor layout using the edge shifting mechanics, the (3) being the manual editing of the floor layouts by the user with the usage of mechanics from the (2) stage and automatic adjustments of rooms.

The main goal of this research is creating a functional computational design tool for architects, mimicking the architectural workflow based on real stages of the design process and joining the generative design with the architect’s experience (Takagi, 2001). To achieve that, the authors created the software for AFPG based on the custom implementation of an HEA. Evolutionary Computation presents the proper balance between the rejection and the faithful adaptation of the natural solutions in the design process. Authors believe that technology should complement the human decision-making process during the design path. The authors also believe that the presented tool allows the use of available technological solutions in a creative way.

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[2] https://youtu.be/YtddGLx1p2g

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Deep Form Finding

Using Variational Autoencoders for deep form finding of structural typologies

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In this paper, we are aiming to present a methodology for generation, manipulation and form finding of structural typologies using variational autoencoders, a machine learning model based on neural networks. We are giving a detailed description of the neural network architecture used as well as the data representation based on the concept of a 3D-canvas with voxelized wireframes. In this 3D-canvas, the input geometry of the building typologies is represented through their connectivity map and subsequently augmented to increase the size of the training set. Our variational autoencoder model then learns a continuous latent distribution of the input data from which we can sample to generate new geometry instances, essentially hybrids of the initial input geometries. Finally, we present the results of these computational experiments and lay out the conclusions as well as outlook for future research in this field.

Keywords: *artificial intelligence, deep neural networks, variational autoencoders, generative design, form finding, structural design*

INTRODUCTION

In recent years, we are witnessing a proliferation of machine learning tools and methods in both academic as well as professional fields. In this paper, we are aiming to present a methodology for generation, manipulation and form finding of structural typologies using variational autoencoders. Machine learning and especially neural networks are already widely implemented for solving problems of geometrical complexity and data manipulation inherent to pattern recognition of 2D images (Krizhevsky, Sutskever and Hinton, 2012) as well as various types of manifolds such as 3D geometry and graphs (Kelly et al, 2018) (Wang et al, 2018). Depending on the problem and the discipline, these manifolds can fall within a wide variety of geometrical domains. However, beyond the training involved in the initial tasks of recognizing patterns to streamline complex processes (Luo, Wang and Xu, 2018) (Yetiş et al, 2018) (Wu and Kilian, 2018), we argue that the most promising implementation techniques of neural networks in design rely on their ability to become generative.

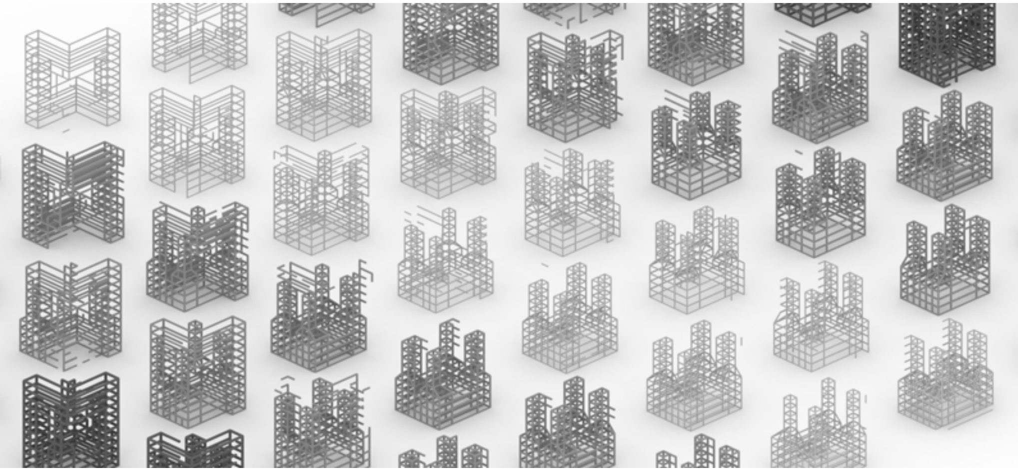


Figure 1
Output of VAE trained model obtained by taking a series of locations within the continuous latent distribution. These locations are then reconstructed following their resulting connectivity map.

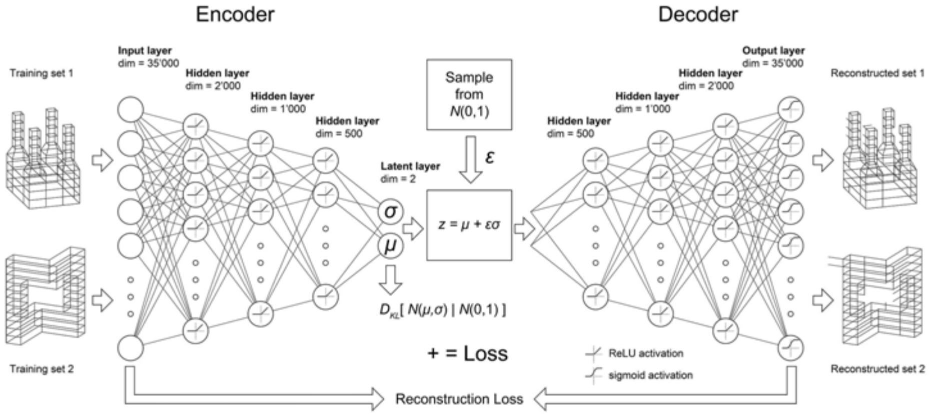
Some work within the design community that maps the potential of this approach has already been conducted (Cudzik and Radziszewski, 2018). Powerful techniques inherent to these models like sampling (White, 2016) and feature vector arithmetic (Radford, Metz and Chintala, 2016) show great promise in the context of design. Variational autoencoders, which are a recent development of neural networks, are shown to be able to generate many types of complex data. Although initially trained on sets of labeled images, proliferated use of these models in wider disciplines has driven the need for working with vector data and 3D geometry (Gregor et al, 2015) (Ha and Eck, 2015). To reduce the dimensionality of the input data, some neural network models transform the raw 3D geometry input into its voxelized representation (Wu et al, 2016).

Our approach involves taking the centerlines of the interconnected structural elements that compose a building to obtain a wireframe that is representative of its core geometry. Represented as a connectivity map, we used this geometry as an input data for a variational autoencoder, opening up a methodology within 3D machine learning that is applicable to the field of structural design. After training on an augmented data set, the network learned to identify various types of wireframes. In the last stage of the process, we made use of the generative capability of the network by sampling new points from the continuous latent distribution that the model has learnt. The autoencoder then outputs their corresponding connectivity maps that result in newly generated wireframes.

VARIATIONAL AUTOENCODER

Our variational autoencoder network is taken directly from the paper "Auto-encoding variational Bayes" by Diederik P. Kingma and Max Welling from 2014 (Kingma and Welling, 2014). We also consulted a very good summary of variational autoencoders and their inner workings written by Kevin Frans from 2016 [2] as well as "Tutorial on Variational Autoencoders" paper (Doersch, 2016). For implementation of the model in Keras we consulted the work by Francois Chollet from 2016 [1]. We adapted the number of neurons in intermediate layers to accommodate for our input layer dimension and added custom parts for data input and output. Code is implemented in Python using Keras as a high-level API for TensorFlow, a machine learning library developed by Google. Our

Figure 2
Diagram of VAE model architecture with 150 million trainable parameters.



variational autoencoder architecture therefore consists of an encoder and a decoder network with a latent layer in between that encodes two latent variables of the probability distribution.

The encoder network consists of the input layer with 35,100 neurons, 3 intermediate fully connected layers consisting of 2,000, 1,000 and 500 neurons respectively. This number of neurons in each intermediate layer is derived from a grid search approach. The decoder network is the inverse of the encoder network, ending with an output layer of the same dimension as the input layer. All neurons use rectified linear unit (ReLU) as an activation function, except in the output layer that uses sigmoid activation. The output of the network is fully reconstructed from the in-between latent layer that encodes the input data probability distribution. Results from the network are directly written into a connectivity map in plain text format, which is later read in Rhino to reconstruct the wireframe geometry.

$$l_i\ (\theta, \phi) = -\mathbb{E}_{z \sim q_\theta(z|x_i)}\left[\log p_\phi\ (x_i \mid z)\right] + \mathbb{KL}(q_\theta(z \mid x_i) \mid\mid p(z))$$

Figure 3
Our loss function is summing two separate losses: the reconstruction loss and KL divergence.

Reconstruction loss is measuring how well do the outputs of the network match the inputs and is calculated as a mean squared error between the two. KL divergence measures the difference between the distribution of the latent variables and a unit Gaussian. Added together, these two losses force the network to generate latent vectors that roughly follow a unit Gaussian distribution (Doersch, 2016). As the latent layer contains only two variables, we can sample the distribution and plot its results on a 2D grid. For network training, we used the GPU cluster at the University of Seville. It took approximately 20-30 minutes to train a network for 25 epochs.

DATA REPRESENTATION

In order to train a variational autoencoder it was crucial to prepare our 3D geometry in a way that can be parsed through the network. This means choosing a most compact way to represent the geometry, avoiding redundancies whilst retaining full information. We call our proposed model 3D-canvas as it consists of a rectangular 3D volume discretized in cube-shaped cells within which the input geometry is contained. Each cell of the 3D-canvas contains labeled connectivity vectors that can be activated or deactivated depending on the input geometry. These connectivity vectors represent wireframe segments in different orientations that are used to approximate the input geometry in 3D space. To keep our data representation compact and without overlaps, we discarded parallel connectivity vectors and chose only 13 for each cell according to Figure 4. For understanding, we included a corresponding Figure 3 that shows the same principle working in 2D space.

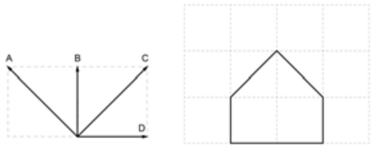


Figure 4
Connectivity diagram for 2D.

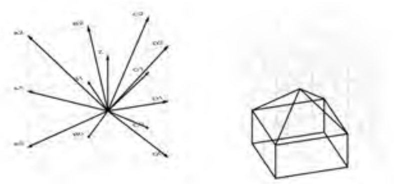


Figure 5
Connectivity diagram for 3D.

At the beginning of the routine, a 3D-canvas is generated "around" the input geometry, so that the full extent of the input can be encoded within it. Wireframe line segments of the input geometry are then snapped to the grid defined by the cube-shaped cells of the 3D-canvas and corresponding connectivity vectors are mapped according to each one of the orientations of the snapped line segment. This process is iterated throughout each cell of the 3D-canvas (which acts as the container of the input geometry) until the full extent of the input geometry is described in this way. This information is then stored in a connectivity map with its corresponding grid coordinate (3D-canvas) and values for the 13 connectivity vectors are marked with a letter and a number indicating its orientation in each cell. To make it easier for a variational autoencoder to train, instead of using a binary value for the presence of a connectivity vector (0 or 1) we used a continuous value representing a percentage with a domain [0, 1]. Our chosen activation threshold within this domain was arbitrarily set to 0.6 and kept for all training samples, which means that values above this threshold indicate the presence of a wireframe segment in that cell, while values below indicate it's absence. Although not implemented in the current model, this continuous value could be used to encode the thickness of the structural wireframe element, where smaller values would correspond to thinner elements and larger values to thicker elements. This principle could be used to encode other structural or material properties as well.

Connectivity map

Parsing the input geometry into a connectivity map was implemented in Rhino using a custom written Python script. The connectivity map itself is stored as a plain text file and read directly by the Python script used to train the variational autoencoder. In order to be used as an input, the connectivity map needs to be "flattened" and the value for each connectivity vector for each cell of the 3D-canvas mapped onto a single input neuron. In our training examples, we used a 3D-canvas with dimensions 14x14x11. The 3D canvas is then composed of 14 cells along the x-axis, 14 cells along the y-axis, and 11 cells along the z-axis. This resolution is sufficient to distinguish structural typologies like arches, wall and surface elements, volumes with cavities, openings etc. and allowed us to design and implement instances of neural networks which are trained for recognition and handling of data pertaining to the field of architectural geometry. With each cell having 13 connectivity vector values assigned to them, the number of input neurons for the variational autoencoder is therefore calculated as 15x15x12x13 = 35,100. Here we calculate with 15 instead of 14 as a dimension, as we need to consider one additional node to define the snapped lines that might be inscribed in the top, rear and lateral faces of the 3D-canvas. As the number of training parameters in a neural network grows with the number of input neurons, this size of the 3D-canvas was at the limit of what we could work with in terms of available computational power. Future improvements to the

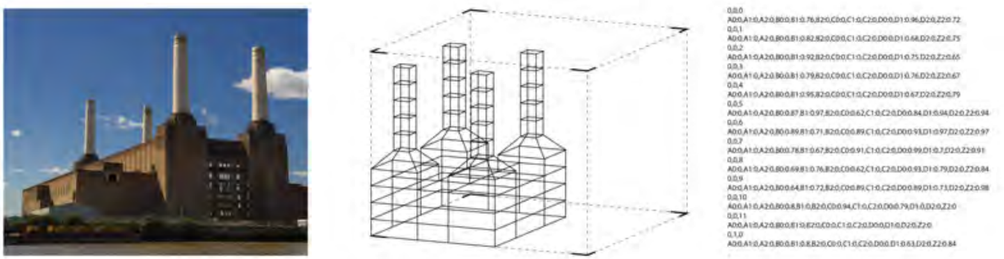


Figure 6
Battersea Power Station, its representative geometry as a snapped set of lines within the 3D-canvas and a part of its corresponding connectivity map.

training model should include a different approach to parsing the 3D input geometry, possibly using a convolutional neural net architecture. This would enable using larger 3D-canvases and correspondingly parsing models in higher resolution while at the same time significantly reducing the number of trainable network parameters.

Data augmentation

Training neural networks of any kind requires large amount of input data. Additionally, this data should ideally be as continuous as possible in terms of raw input values. For images of 3D objects, this continuity implies gradual changes in translation, rotation, scale, color and brightness values of the input data. Artificially added noise on the level of pixels can as well help the network to learn the underlying meaningful features in the data. A technique called data augmentation is often used in order to enlarge the number of training samples by artificially adding variation to the input data (Goodfellow, Bengio and Courville, 2016). In our model, the number of initial training samples was only two, corresponding to two input models between which the autoencoding was to be done. To augment our training data, we used simple random translation of the input models inside the 3D-canvas to increase the number of training samples to 3,000. At the beginning, we also experimented with rotation, but this was not successful, as rotations in a rectangular grid could not be implemented as gradual transformations but only as 90-degree "jumps". These discretely rotated samples would be considered as separate training sets by the neural network and slow down the training. We found similar limitations for scaling the input models. Based on these findings, we used only discrete randomized translation to augment the training data. Future improvements of the model could include introduction of noise in the form of randomly activating or deactivating connectivity vectors based on some small probability value. This would increase the robustness of the variational autoencoder training process and make the network better learn features that are invariant to the noise. Finally, we exported the complete training set with augmentation into the connectivity map from which it can be read into the training model.

CASE STUDIES AND RESULTS

As mentioned previously, for training we ran tests where we used input models augmented to 3,000 samples each, totaling 6,000 samples for the two-input models tests and 9,000 samples for the three-input models tests, at each epoch. Variational autoencoder network then learned the underlying distribution of the input data, mapping each initial data set (the learnt input geometries) onto a continuous latent space. Because this latent space is continuous and two-dimensional (there are only two latent variables), we can sample this space and plot the results on a grid, thus obtaining the geometries that lay in between the distribution of the original inputs. Due to their "bottleneck" architecture, autoencoders are forced to learn compact representation of the input data (Goodfellow, Bengio and Courville, 2016). This process can most efficiently be achieved by learning the underlying translationally invariant high-level features in the data and map it into a higher-dimensional latent space. Assumption is that all geometries that share certain higher-level features (like a spatial gap under the bridge or an arch or protruding thin volumes of towers from a castle for example) are mapped as close points on a higher-dimensional manifold in the latent space (Sohn, Lee and Yan, 2015).

Variational autoencoders enable us to sample this higher-dimensional manifold in a continuous manner and to obtain variations or hybrids of initial input geometries, success of which we can directly evaluate visually by examining the geometries sampled from the distribution. Thus, we obtained interpolated geometries resulting from the sampling of the positions within the learnt distribution of the original input models. By being able to identify positions representative of specific geometric instances within the latent space, the possibility for thinking about pseudo-semantic operations with vectorized geometric entities can be considered as further implementation of this technique. Following our 3D-canvas and connectivity vector approach, this might be challenging due to the high n-dimensional vector that is representative of the geometry of each sample within the dataset. We hope that this paper can help exploring further methods that allow for this type of vector-based geometric operations.

VAE experiment no. 03. Wireframes of 2-distinct input buildings: Battersea Power Station (in purple) and CCTV (in yellow). Top view of chart representing the learnt distribution in latent space, together with reconstructed wireframes from a grid of sample points taken from this distribution. With only 25 epochs, the output proved smooth transitions in-between the reconstructed samples resembling the original input. KL = -0.5

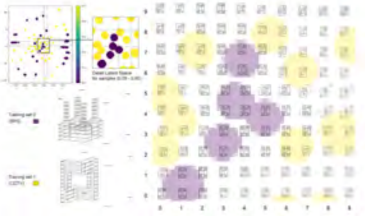


Figure 7
Experiment no. 03

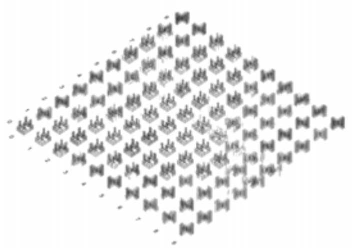


Figure 8
Experiment no. 03

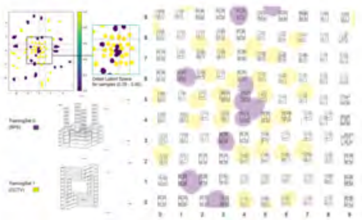


Figure 9
Experiment no. 05

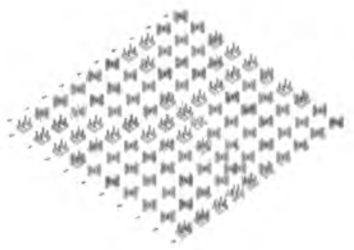


Figure 10
Experiment no. 05

VAE experiment no. 05. We have now increased the training of the model, sampling points from the latent space after 75 epochs. The model seems to be over-trained (after only 50 epochs more) and to over-recognize the outputs in latent space, offering no smooth transition in-between the grid of reconstructed wireframes. KL = -0.5

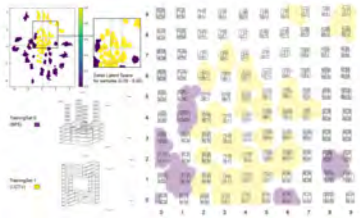


Figure 11
Experiment no. 06

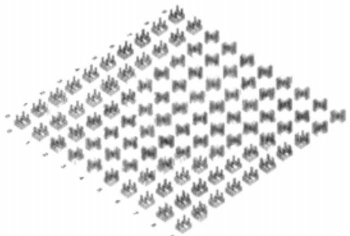


Figure 12
Experiment no. 06

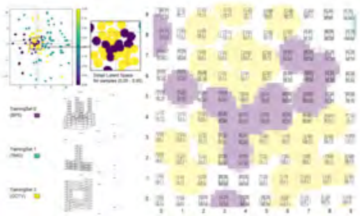


Figure 13
Experiment no. 13

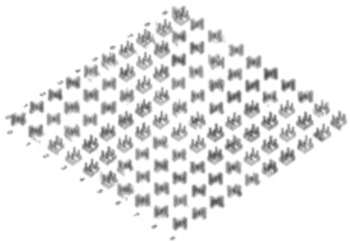


Figure 14
Experiment no. 13

VAE experiment no. 06. We sample points after 25 epochs, and change KL to -10.5. The resulting distribution is mapped into clearly defined regions. Similar to Experiment no. 05, the model seems to over-recognize the outputs in latent space, offering no smooth transition in-between the grid of reconstructed wireframes.

VAE experiment no. 13. Wireframes of 3-distinct input buildings: Battersea Power Station (in purple), Tate Modern (in cyan) and CCTV (in yellow). Top view of chart of latent distribution, together with corresponding reconstructed wireframes. With only 25 epochs, the output proved smooth transitions in-between the reconstructed samples. KL = -0.5

VAE experiment no. 15. We have increased the training of the model, sampling points from the latent space after 75 epochs. Again, the model seems to be over-trained (after only 50 epochs more) and to over-recognize the outputs in latent space, offering no smooth transition in-between the grid of reconstructed wireframes. KL = -0.5

In the series of experiments presented here, we are working with models that handle around 150 million parameters, whilst only training with 6,000 and 9,000 samples respectively as the dataset for the corresponding tests. From our experience with training the models, the number of samples in the dataset should be around 10% of the number of parameters in the model, which makes 15 million samples for the models that we used an optimal number. Therefore, further work on these models would require a greatly increased dataset in order to have a better balance of training and validation.

CONCLUSION AND OUTLOOK

Due to the growing international academic interest in generative machine learning methods and its wide commercial applications, it is clear that the workflow presented in this paper is just the beginning of a burgeoning field. Although developed 5 years ago, the use and usefulness of variational autoencoders in the context of architectural design remains mostly unexplored. We hope that this paper will show the potential of these methods to a wider design audience, specifically in application to working with 3D geometries. Unfortunately, this is as well one of the technical bottlenecks in extending the application to larger geometries, namely the fact that the amount of input parameters scales proportionally with the bounding volume of the input geometry. This makes working

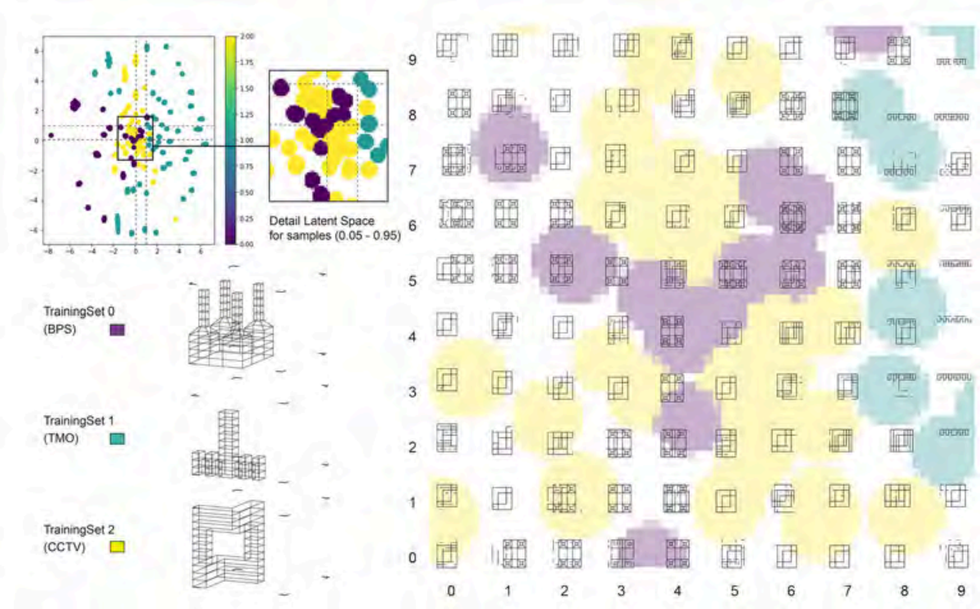


Figure 15
VAE experiment no. 15: Battersea Power Station, Tate Modern and CCTV.

with large bounding boxes unpractical due to long network training times, even if the training is conducted on a GPU cluster. Existing techniques like introducing convolutional layers into the variational autoencoder could be used to solve this problem. To improve the learning of the model proposed in this paper, it would be useful to use a data set not derived from few augmented instances, but rather from a larger repository of 3D wireframe geometries of structural typologies. The authors of this paper are currently not aware of the existence of any such repository.

In addition, to improve the quality of generated geometries, switching to a completely different neural network model could be called for, as generative adversarial networks (GANs) proved to be even more powerful in terms of learning higher-level features of the data and using this to reconstruct plausible instances of it. In that sense, GANs could be used instead of variational autoencoders as design generators. Future research should focus on pros and cons of using either of these models, especially in terms of current research being conducted on merging the two models to parse 3D geometries (Wu et al, 2016). Finally, as already mentioned earlier in the paper, continuous values in variables representing connectivity vectors could be used to encode other structural or material properties of the wireframe members like thickness, material strength, etc. This would contribute to pushing this research towards a more material driven design with holistic structural understanding, rather than just focusing on the underlying geometry.

The proposed workflow challenges designers to acquire a critical perspective of the impact and potential of AI in our society and design practices. We believe that generative neural network models have a large potential to redefine how architects and designers work with architectural precedents, namely to use them directly as data for design generation.

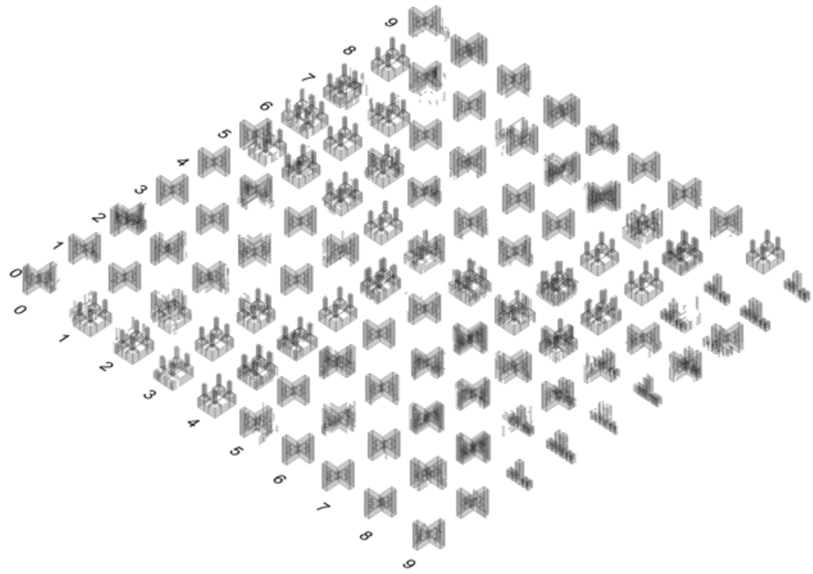


Figure 16
VAE experiment no. 15: Reconstructed wireframes from a grid of sample points taken from this distribution.

Figure 17
Output of VAE trained model obtained by taking a series of locations within the continuous latent distribution - CCTV on the left and Battersea Power Station on the right.

Work presented in this paper shows the potential of such techniques and the future of AI in the context of architectural geometry generation and the potential that bespoke AI-based tools for architects can bring to the field of structural deep form finding.

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Steps towards AI augmented parametric modeling systems for supporting design exploration

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Dataflow parametric modeling environments have become popular as exploratory tools due to them allowing the variational exploration of a design by controlling the parameters of its parametric model schema. However, the nature of these systems requires designers to prematurely commit to a structure and hierarchy of geometric relationships, which makes them inflexible when it comes to design exploration that requires topological changes to the parametric modeling graph. This paper is a first step towards augmenting parametric modeling systems via the use of machine learning for assisting the user towards topological exploration. In particular, this paper describes an approach where Long Short-Term Memory recurrent neural networks, trained on a data set of parametric modeling graphs, are used as generative systems for suggesting alternative dataflow graph paths to the parametric model under development.

Keywords: *design exploration, visual programming, machine learning*

INTRODUCTION

Exploring multiple design alternatives is an integral part of the early design process. Dataflow parametric modeling environments have gained a general appreciation as exploratory tools due to them allowing variations of a design to be explored by adjusting the parameters of its parametric model schema. The parametric modeling environments that extend our CAD tools are employing the single state model of interaction (Terry and Mynatt 2005), therefore typically these design variations are being accessed sequentially.

To streamline the sampling of the design space defined by a parametric model schema and support the comparison of these design alternatives in parallel, both industry and academia have been exploring parameter based interfaces (Mohiuddin et al. 2017, Tomasetti 2017, Autodesk 2018). These interfaces extend such parametric modeling systems and provide automatic mechanisms for generating and visually juxtaposing design variations. Via these mechanisms searching into the design space defined by the parametric model schema and evaluating the variational alternatives becomes more accessible.

Even though such parametric modeling systems facilitate variational exploration, they are not flexible when it comes to working on a design alternative that involves changing the parametric model structure (Chaszar and Joyce 2016). To build a parametric model, designers need to prematurely commit to a structure and hierarchy of geometric relationships and data structures, which is hard to alter during the design process. The cognitive load for making changes to the topological structure of the parametric model schema is big and in many cases, one would need to build the model from scratch (Holzer et al 2008, Turrin and Stouffs 2011). Therefore designers can easily become locked-in (Harding and Shepherd 2017) working on a specific parametric model schema and not attempt to explore different conceptual design alternatives.

The research reported here takes the view that if it is to envision our parametric modeling systems as design exploration tools, they should support designers beyond just variational exploration. Towards this direction, this research investigates how dataflow parametric modeling systems can be augmented to assist designers in considering alternative paths during the process of developing a parametric model. The strategies of *backup*, *recall* and *replay* which traditionally drive forward the designer's exploration action (Woodbury and Burrow 2006) are being revisited and reimagined via the use of machine learning models; the objective is to employ the computational system with the ability to suggest ways to the designer for expanding the design space under consideration.

In particular, Long Short-Term Memory (LSTM) neural networks are being proposed as a model capable of learning order dependence and spatial structure of parametric modeling directed acyclic graphs (DAGs). Once the network is trained, it can serve as a generative system for synthesizing new sequences of nodes based on an arbitrary input node sequence. The scope of this paper is to evaluate the potential of this approach. It is the first step towards the bigger vision of computationally supporting designers on investigating alternative parametric model schemas that could potentially perform better in terms of their set criteria and requirements.

First, exploration in the context of dataflow parametric modeling systems is defined as the transformation of the DAG's design space description; relevant precedent work on design space expansion is presented. Next, the process of training a machine learning model on a dataset of collected graphs, and using the trained model as part of a graph synthesis system for transforming the design space description of the graph is described. The potential of the machine learning model to learn structural information from previously created graphs and used as a synthesis tool is discussed. The paper concludes by highlighting future steps and improvements.

RELATED WORK

Design space is the network of the possible states a design can take. A parametric modeling graph defines a design space out of the combinations of the graph's input parameters. The geometry and numerical primitive units, the topological relationships and constraints, the manipulative functions, as well as the parameter ranges, formulate the description of the design space of the parametric model schema. Due to the structured nature of a parametric model schema, as the graph evolves, the description of its design space becomes fixed, a closed system inflexible to adapt to changing requirements.

When all variables and their relationships are defined a priori, the interaction with the design space is simply a search to determine feasible, satisfying or optimal parameter values (Gero 1994). Design, however, cannot be simply assisted by a search process; at any point, changing requirements and goals may indicate a different design space to be searched. Therefore, computationally assisted exploration needs to involve the process of determining the space within which to search, either by creating new design state spaces or by modifying existing ones (Gero 1994). Gero (1994) proposes that this can be accomplished by creating new symbols out of prior ones by way of addition, substitution or evolutionary combination.

Engineering design demonstrates research work around design space expansion via addition or substitution of new variables and features. Domain-specific heuristics are typically used to control the process of modifying the models or representations of a design (Aelion et al 1992). Cagan et al (1991), for example, use a library of predefined design space expansion techniques as the means for modifying the design topology and discovering innovative solutions. The suggested methodology assumes a knowledge representation of the design problem based on the basic, primitive propositions and assumptions. The expansion techniques are defined as mathematical operations to manipulate the knowledge representation of the problem. Optimization is used to decide which expansion technique may lead to improved designs. In a similar direction, Gero and Kumar (1993) demonstrate how feasible or improved solutions can emerge by introducing new design variables to optimization problems that due to conflicting constraints have no feasible solutions.

In the cases mentioned above, the design space description of the problem is already fixed. The methods for mutating or augmenting this design space are also a priori defined and opinionated towards specific ways of solving a particular class of problems. To make such approaches more generic, Gero and Kumar (1993) propose the use of analogical reasoning - finding precedents of similar past design cases and choosing variables from those cases to expand the design space under consideration.

Research work from the data visualization domain demonstrates relevant efforts particularly targeted to visual programming environments. Systems for creating visual programming pipelines for data exploration assist users in the process of constructing new pipelines by reusing pipeline data from a database of previously created visualization pipelines. Pipeline fragments can be used as templates to query the database, locate, and merge relevant pipelines that match certain criteria (Scheidegger et al 2007). Also, given a partial pipeline under development, sets of likely pipeline additions can be predicted by computing correspondences between existing pipeline subgraphs from the database (Koop et al 2008). These approaches show potential towards assisting users considering wider design spaces or modifying existing ones, however, they are based on matching exact precedents from the database.

Falling into the category of design space expansion via evolutionary combination, Harding and Shepherd (2017) developed an approach they call meta-parametric design. They propose automating the synthesis of directed acyclic graphs for parametric models - based on Cartesian Genetic Programming - as a way to widen the exploration of different design concepts. A graph is represented by an integer-encoded string that includes all its numeric, functional, and topological information. This string representation constitutes the genotype for an evolutionary algorithm that via mutation and crossover drives the automated generation of graphs. The limitation of this approach arises from the fact that the user needs to decide a priori what components will be used. This choice determines the geometry vocabulary available to the algorithm and therefore directs the type of results achieved. Also, the generator produces graphs of higher complexity than manually built models; due to the lack of abstraction, they are inefficient and not easily readable by humans (Joyce et al 2017).

SYNTHESIZING DATA DRIVEN COMPLETIONS

In a parametric modeling graph, nodes represent computational functions, let's call them modules, and edges represent how data flows through the modules. More formally, a parametric modeling graph is a directed acyclic graph $G = (V, E)$ where V consists of a set of modules and E is a set of connections between modules in V. A module is an object that contains a set of input and output ports through which data flows in and out of the module. A connection between two modules v_a and v_b, connects an output port of v_a to an input port of v_b.

Given this context, the problem of deriving partial completions for the graphs can be defined as follows. Given a partial graph (subgraph) H we wish to find a set of completions that reflect the node structures that exist in a collection of completed graphs. The completions comprise a sequence of nodes that can be connected to each other in a meaningful way both syntactically and semantically. VisComplete (Koop et al 2008) proposed a solution to this problem by using exact templates from the training data to make predictions, by counting exact matches between the recent history and the data set. This paper's approach, on the other hand, involves a machine learning model that uses its internal representation to perform a high-dimensional interpolation between training examples. The objective is that the model synthesizes and reconstitutes the training data in a complex way with the possibility for node sequences to emerge that do not necessarily exist in the dataset.

Long Short-Term Memory (LSTM) recurrent neural networks are trained on a data set of previously created graphs and are used as generative systems for suggesting alternative dataflow graph paths to the parametric model under development. LSTMs are widely used for natural language processing having been proven capable of learning order dependence and spatial structure of text. This work employs methods used for training LSTM networks for text generation (Graves 2013, Sutskever et al 2011) and approaches that generalize these methods from sequences of words to graphs (Perozzi et al 2014). It adopts these methods to the case of directed acyclic graphs (DAGs), the representation used by our dataflow parametric modeling environments.

The prototype system consists of three components a) the data parser component, which converts the graphs from the training dataset to sequential data, b) the trainer component, which is responsible for the training process of the neural network, and c) the synthesizer component, which queries the trained model and performs topological changes, node, and link additions, to the directed acyclic graph. Figure 1 displays an overview diagram that demonstrates the process involved in each component. They will be described in more detail in the following sections.

Parsing graphs to sequential data

Like any other CAD tool, a parametric modeling visual programming environment is a system that employs computational mechanisms to effect change. While building a parametric modeling graph, the progressive addition of nodes produces new spatial objects or changes to spatial objects by manipulative operations like arithmetic operations and geometrical operations. The sequence of spatial changes is continuous (Krishnamurti and Stuffs 1996); with every node addition, we derive a new spatial object from a given object. Therefore every manipulative operation is dependent on the history of operations and the structure and hierarchy developed so far in the graph. This fact highlights the need for learning generative models over graphs that can capture their relational structure and order dependence.

Recurrent neural networks (RNNs) are a class of such models that can be trained for sequence generation. RNNs contain cycles that feed the network activations from a previous time step as inputs to the network to influence predictions at the current time step. This adds "memory" to the network that allows it to learn the ordered nature and relationships of the sequential input data. We are using a specific type of RNN architecture, called Long Short-Term Memory (LSTM) designed to be better at learning long-range structure than standard RNNs (Hochreiter and Schmidhuber 1997).

An important challenge we need to address is designing an invertible way of converting a parametric modeling graph structure to a sequential representation (linearization); this way we can treat sequences as sentences in natural languages and use the LSTM language models and methodology. There is a significant amount of work from the natural language processing and program synthesis community. For example, Vinyals et al. (2014) flattened a tree into a sequence following a depth-first traversal order and then modeled parse tree generation as a sequence to sequence task. Other efforts use more domain-specific linear representations as fingerprints to represent graphs (Gomez-Bombarelli et al 2018). For this first iteration of our experiment, we parse the graph into all possible linear paths of nodes and we model the problem as a sequence to prediction task. Given a corpus of examples of linear paths

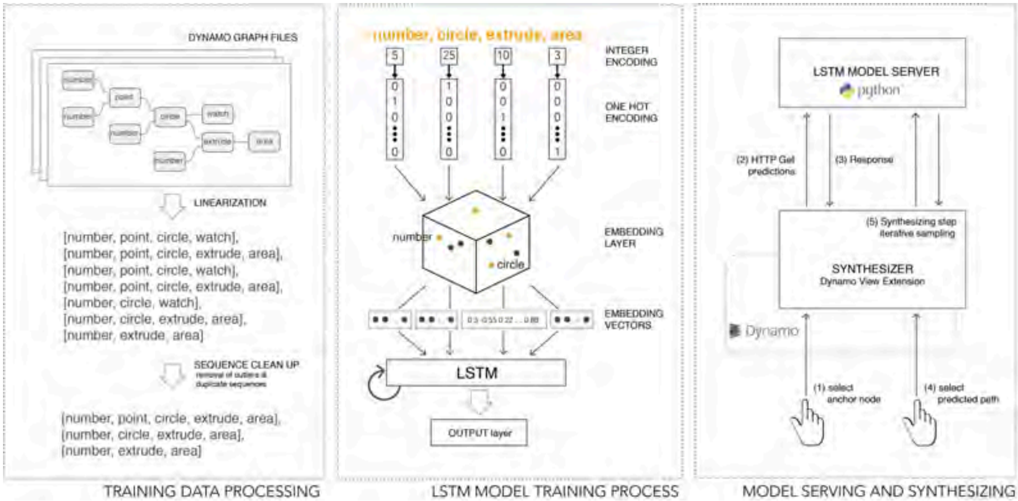

Figure 1
Overview diagram.

extracted from a data set of existing parametric modeling graphs, generate new sequences of nodes that have the structural properties of the corpus. Our selected approach for how to synthesize back the predicted sequences into the graph structure will be explained in the following section.

Model architecture and training

An LSTM neural network is a kind of recurrent neural network with a recurrent, hidden layer of memory blocks (Hochreiter and Schmidhuber 1997). Each memory block contains several self-recurrent linear memory cells. The self-recurrence on each cell enables it to accumulate numerical values over a series of iterations of the network. The accumulated data is passed through a nonlinear function. Each block contains three gated sigmoid units and can regulate the flow of information. These gates can learn which data in a sequence is important to keep or discard; this way the relevant information is being passed down the long chain of sequences to make predictions. The complete equations for the LSTM network are beyond the scope of this paper.

The network consumes the sequence of nodes in a left-to-right sweep, creating one-hot encoded vectors in memory; these vectors are high-dimensional and sparse. In our training set, we have 600 unique nodes; this means that, when using one-hot encoding, each node will be represented by a vector containing 600 integers. In order to do this computationally more efficient and to have the network learn similarities between nodes, we use an embedding layer (Mikolov et al 2013). This allows us to capture relationships in the graph structure that are very difficult to capture otherwise. The use of the embedding layer helps the network learn a representation of nodes in which nodes that tend to appear adjacent to each other are closer in the vector space.

To summarize, the network architecture comprises 3 layers: a) An embedding layer that maps the discrete representation of a node, i.e. the one-hot encoded vector, to a semantic representation, b) This semantic representation is then fed to an LSTM layer which generates a state based on the previous state and current input. This combination of the states provides the context to our model, and c) A layer that maps this generated state to a set of probabilities. We train two separate models, one feeding the input sequences of nodes in a left-to-right sweep and one feeding them backward; this way we can retrieve predictions for downstream and upstream nodes respectively.

Generating suggestions

During graph derivation, the synthesizer component adds new structure to the existing graph, specifically a new node, and the probability of that addition event depends on the history of the graph derivation. We train the model as a predictive model, but we use it as a generative model to generate entirely new plausible sequences of nodes. The predictions are probabilistic; novel sequences can be generated from the trained network by iteratively sampling from the network's output distribution, then feeding in the sample as input at the next step. Although the network itself is deterministic, the stochasticity injected by picking samples induces a distribution over sequences. Since the internal state of the network depends on the previous inputs, the final distribution obtained is conditioned upon the previous inputs as well.

Each synthesizing step generates a downstream sequence of three nodes by querying the model trained on forward sequences. In each iteration, a new downstream node is added and linked to the anchor node. If there are available input ports on the newly added node, then the system queries the model trained on the backward sequences. The iteration completes when the newly added node is designated as the new anchor node (Figure 2). For every request for a downstream prediction, all linear paths that the upstream graph that leads to the anchor node can be parsed into, are taken into account. Similarly, for every upstream prediction request, all downstream graph paths are taken into account.

Let's take a closer look at how the system synthesizes the predictions for the sequences into a node prediction that reflects the graph structure. Given a parametric modeling directed acyclic graph G we want to know which next node could be a possible addition to progress the series of spatial transformations. We can express the probability of an incoming node addition as $P(n|G)$. The question is how can we express this in a computationally feasible manner. To accomplish this, we consider a simplified base case. Let's denote any of the leaf nodes of the graph (nodes that do not have any successors) as our anchor node; we are seeking the next node that is a possible addition to that anchor node. Next, we consider the upstream subgraph that leads to this anchor node and we create the set of node sequences that form all possible directed paths $P = \{p_1, p_2, \ldots p_n\}$ that lead to the anchor node. Given the set of upstream paths, the probability of a single node is the measure of how likely it is that node to show up, given the upstream paths. To compute the

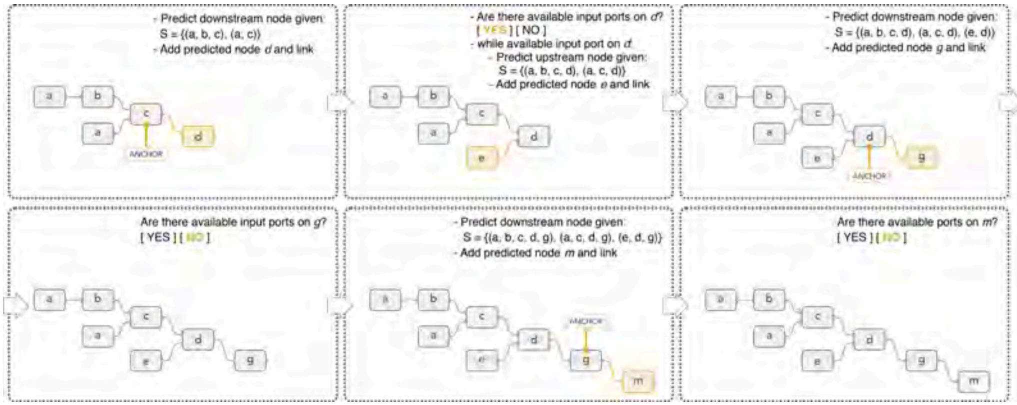

Figure 2
Graph derivation during a synthesizing step of 3 iterations.

likelihood of a single node we need to take into account the information given by all upstream paths. In other words, the probability of an incoming node can be expressed as the joint probability of all upstream node sequences:

$$P(n|p_1, p_2, \dots p_n) \tag{1}$$

The formula is commonly used to describe graphs in the bayesian world. For the need of this paper, we make a simplifying assumption that the upstream paths are independent of each other. This reduces our expression to:

$$P(n|p_1, p_2, \dots p_n) \propto P(n|p_1)P(n|p_2) \dots P(n|p_n) \tag{2}$$

Implementation

The data parser component is an executable that runs Autodesk's Dynamo® headless (without loading the graphical user interface) to load each Dynamo file, parse the in-memory graph data structure of each model, and extract all graph linear paths. The training data set comprises Dynamo graphs aggregated from the web; most of them include example workflows, training material and samples from the Dynamo Primer and Dynamo Dictionary repositories. The parsing process resulted in a training set of 6500 node sequences. The sequence size varies between 2 and 32 nodes.

The trainer component is developed using the Keras API running on top of TensorFlow®. As mentioned above two models are being trained, one using the extracted linear paths and one using the same paths in the reverse direction. Each training run took 22 minutes on an NVIDIA Tesla K80 GPU processor.

The synthesizer component consists of two parts: the server, that serves the two trained models and the synthesizer client. The server listens for prediction requests from the client, queries the trained models and returns a response to the client. The body of a request contains the set paths for which a downstream or upstream node is requested. The body of the response contains a mapping of each node to the combined probability given the set of paths. The synthesizer client is an add-on to Autodesk's Dynamo® developed as a View Extension, which sends requests for downstream or upstream node predictions to the model server. The synthesizer client provides the ability to the user to designate a node as the anchor node for the synthesizing step. The moment the user selects an anchor node the system automatically returns a list of possible paths and populates the predictions list on the synthesizer client window. When the user selects a path, a synthesizing step takes place and the generated nodes and links are added to the Dynamo editor by the synthesizer client.

INITIAL RESULTS

The described work is a first step towards the bigger objective of augmenting parametric modeling systems towards design exploration. The goal was to evaluate whether the proposed approach and in particular, describing parametric modeling graph synthesis as a sequence prediction problem, is plausible. Initial tests using the synthesizer system with the trained models have been positive, although there is still much work to be done to understand the potential use of this method and its applications. We believe that this work can inspire the application of machine learning to research related to design space expansion and content creation in the context of our parametric modeling environment.

Overall, the model has demonstrated successful results in learning order dependence and graph structure. In most of the cases, the predictions are semantically and syntactically meaningful. Note that the focus at this point is not to evaluate whether we can get complete recommendations for design ideas. This is meant for future work and requires a system capable of goal-oriented predictions and sampling. Also, the quality of the predictions is largely dependent on the training dataset; a curated training graph data set of bigger complexity and theme consistency, for example, is expected to yield better results.

The examples in Figure 3 demonstrate the be-

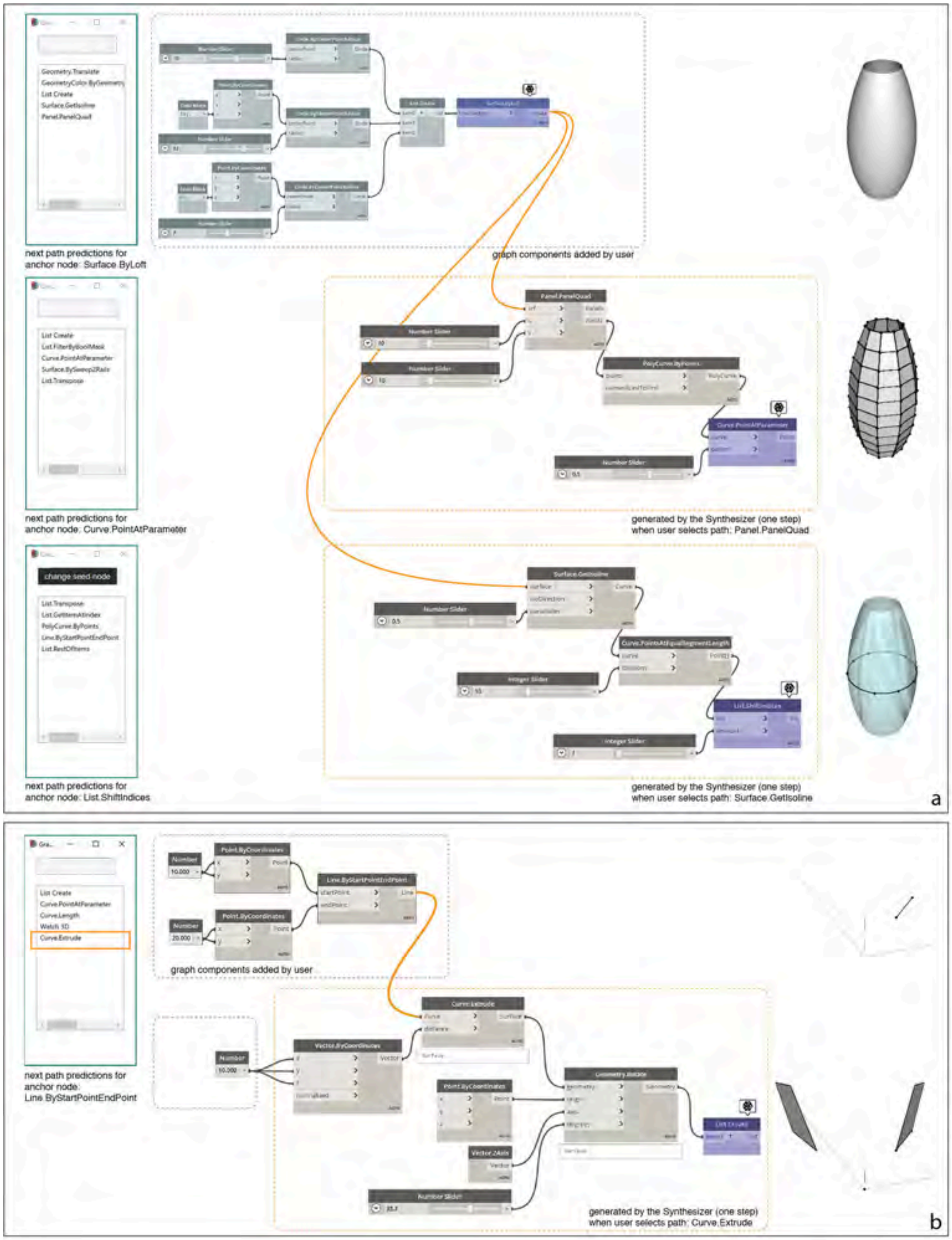

Figure 3
Examples of a synthesizing step. On the left of each graph, the synthesizer's client window displays a list of possible paths given the designated anchor (node in purple). The values of automatically added input nodes (numbers and sliders) were set by the author after the synthesizing step.

havior of the system. Each example shows a synthesizing step. For each synthesizing step, the synthesizer client performs 3 iterations. In each iteration, the forward model is being queried for a downstream node prediction and the backward model for an input node prediction if the predicted downstream node has input ports available. Example *a* shows two alternative paths for the same upstream partial graph and designated anchor node. Example *b* showcases the ability of the system to synthesize data in complex ways that do not necessarily show up in the training dataset. The system links *Curve.Extrude* to the existing *Line.ByStartPointEndPoint*; this is a novel sequence that the system has not been trained on and is a meaningful sequence both semantically and syntactically.

Figure 4 demonstrates the system being successful in learning order dependence and context. The transformative operations in the two graphs are the same, but while the upper graph manipulates a single generated rectangle, the lower one manipulates a list of rectangles. The returned predictions, given *Curve.ExtrudeAsSolid* as the anchor node, show that the system has learned to identify such a contextual difference. In the case of the list of rectangles, the system suggests mostly downstream nodes that correspond to list operations.

FUTURE WORK

There is much potential for development and improvements. These include the following:

- Linearizing the graph to node sequences requires the additional work of merging the predictions for the different paths back together to form the graph structure. Ideally, we would prefer a linear representation that reflects the graph structure as a whole. Other linearization approaches from the machine learning literature, like depth-first traversal order (Vinyals et al 2014) or topological sorting of the graph (Li et al 2018) are worth investigating further.
- A training sequence is composed of integer identifiers corresponding to the node names. The model learns node to node dependency but no output to input port dependency. Therefore the synthesizer component adds links between existing and predicted nodes by trial and error. Incorporating information about input and output ports in the training sequence can improve the syntactic and semantic consistency of the predictions and improve the synthesizing process.
- Synthesis occurs at the node level; this makes it more challenging to lead the generation towards an objective. Experimenting with different degrees of decomposition of the graphs and a more modular approach could be beneficial. For example, each data point in the input sequence could maintain more functionality, i.e. a set of nodes that are semantically related. This way, less potential

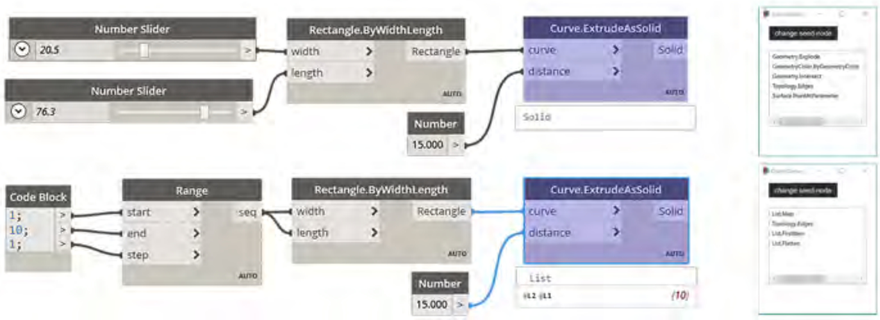

Figure 4
Predicted downstream nodes for the same anchor node given different upstream context.

for variation is afforded, however, less work is required for correct semantic and syntactic matching.

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Challenges - EDUCATION AND RESEARCH

Computational Design Thinking for first year architectural design studios.

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Digital design tools are actually changing the way we design architecture, even if we never choose to use any software. This paper examines and proposes an initial design approach towards Computational Design Thinking for first-year architecture students, without the use of any parametric software. It investigates some of the main points of a Computational Design Thinking approach and then proposes a method for teaching design studios. The method refers to digital design tools / software we use as architects, introducing ways to manipulate physical form, almost the same way that digital design software manipulates digital models. Finally, the paper documents the outputs and evaluates the application of this method in teaching first year design studio in a UK university.

Keywords: *Diagram, Generative Design, Transformations, Physical and Digital Modelling, Computational Design Thinking*

INTRODUCTION

The term Computational Design Thinking, initially introduced by Terzidis (2006), is used to describe an approach where digital and parametric design media used as design tools for architectural synthesis (and not as mere representational tools, which Terzidis (2006) calls "Computerisation"). The method discussed in this paper directly aligns with Pask (1969) and the Cybernetics theory; especially the needed mapping of any steps in a design process, as well as adding feedback in a process that is cyclical, as the systems theory by Wiener (1969) proposed.

The logic of transformations, that digital architecture theory and generative architectural design drew form the theory of form creation -Morphogenesis- in biology and Thompson (1917), is another point of reference in form-finding. Today, Leach (2009) discusses how the theory of Morphogenesis has crucially affected digital and parametric design theory and practice. At the same time, the method uses an important tool that allows architects to map a design process; the diagram, as Eisenman (1999) and Lynn (1999) introduced. The diagram has now become a design method globally.

Menges (2011) proposed that any process of form-finding should include the instructions of the process itself. Also the complexity inherent to parametric or algorithmic design relies to a great extent on the codification of form (Marcos 2010). For this reason, in the discussed method, the commands used to manipulate form are documented in each step, as an analogue way to write a "code" for the transformations. The steps to be followed in Phase 2 of the method application include a final CAD-CAM convergence (Kolarevic 2003).

EDUCATIONAL CONTEXT

In reference to digital architectural design pedagogy, there are already examples of using both digital and physical modelling iterations methodologies within final year design studios of undergraduate architectural studies, but none in the very first year of architectural studies.

An example of advanced design regarding Generative design pedagogy in the third year of teaching architecture, is described in the book Generative Design by Agkathidis (2015). In this book, students that already had some knowledge of architecture and digital design software used for form-finding, such as Rhinoceros explored Generative Design approaches.

A pedagogical approach that focuses on the use of the diagram is discussed by Maldonado (2014) in Digital Recipes: A Diagrammatic Approach to Digital Design Methodologies in Undergraduate Architecture studios. This paper differs from these examples as it is focusing at even an earlier stage of architecture studies; the first year and requires no prior knowledge of architecture or digital design tools.

An example of digital modelling techniques in architectural studies is the textbook Digital Design Exercises for Architecture Students by Johnson & Vermillion (2016). This paper aims to take the textbook approach a step further, proposing a method that focuses on the design thinking, regardless of the design tools used.

THE METHOD

The method was applied in design studio teaching during the whole first year of architectural studies in a UK university and is split in two phases. A part of Phase 1, was presented at the SIGraDI conference in 2016. Phase 1 focused on transformations of physical models as a way to map the design process in a controlled way, the same way any visual parametric software creates a map of interconnected design parameters that control and manipulate geometries.

During each of the two semesters of the academic year, students were asked to design their main studio project using the proposed method. The first semester-phase had three design projects and the second-semester had one design project.

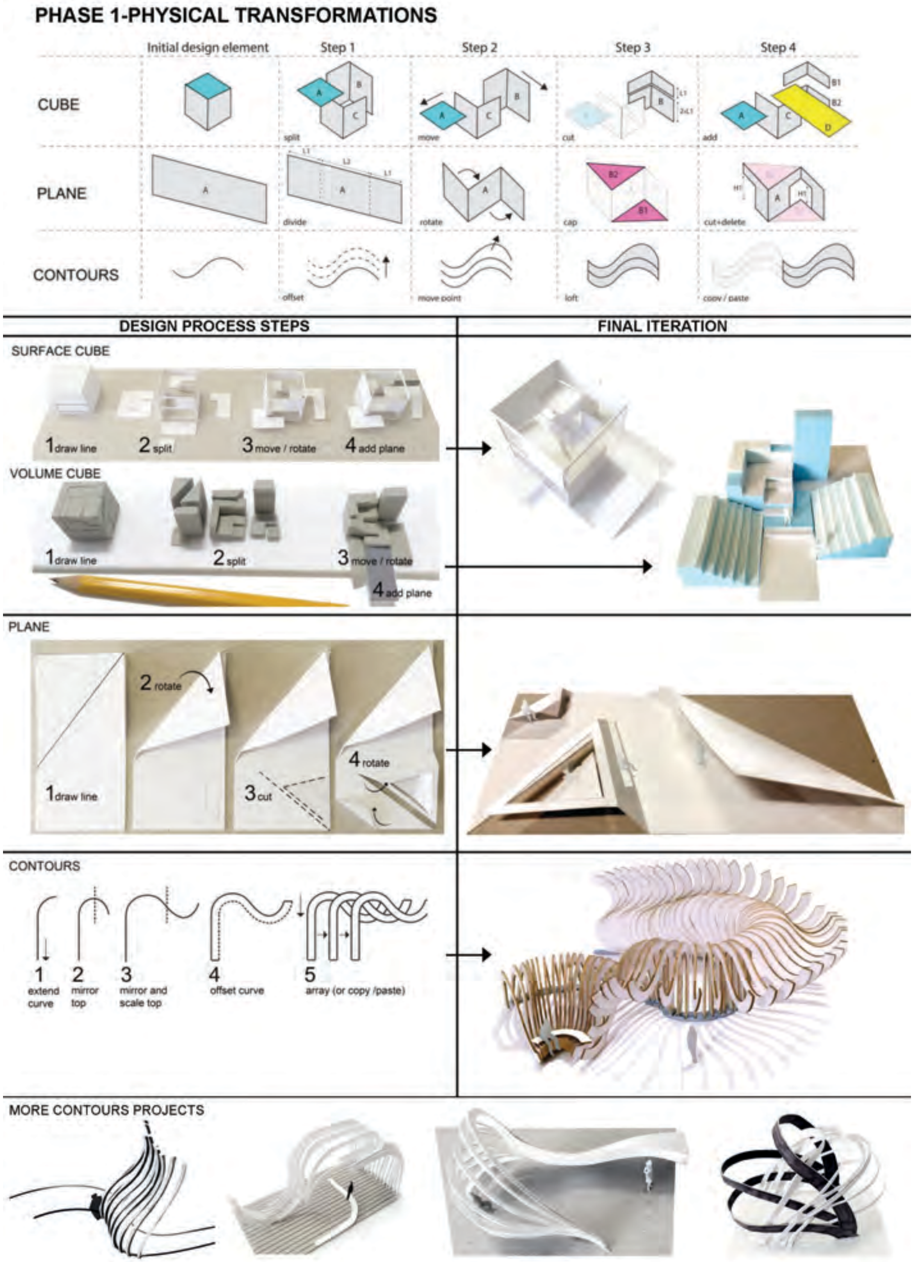
Phase 1 is using maybe the most basic tool for architectural design: physical modelling. Students were asked to develop a number of spatial transformations, using only four consecutive numbered steps. They had to physically transform a specific initial geometry (a cube, a plane and a contour curve) during three design studio workshops-projects in semester 1 of their studies. Students had to transform their initial geometry (for example the cube) using verbs and commands found in most form-finding design software such as cut, split, trim, move, rotate, scale, stretch, offset, copy, paste.

This way the instructions of process are included in the process itself, as Menges (2011) discusses. The results of phase-semester 1 were a series of physical models for each of the cube, surface and contour workshops. All four transformation steps were documented with physical model photos and 2D diagrams, which mapped the design process, from initial geometry, to final result. (Figure 1).

Beyond documenting their design process - probably like any other first-year design studio project- students also produced sketches, axonometrics, diagrams, as well as plans and sections, for each of the three workshops - projects. It is important to state here that the deliverables at the end of each workshop-project, were more than physical models, since the course has to comply with the RIBA and ARB requirements of teaching first-year design studios in the UK. This means that other than the design process presented here, students had to also think about pragmatic architectural issues regarding their design project, such as programmatic distribution, circulation, tectonics and materiality, to name a few.

Phase 2, like the previous phase, focuses on transformations in order to create architectural space, while mapping each of the numbered steps of the design process. The difference is that In this phase the transformations are digital and that students had to solely use a digital design software used broadly for form-finding: Rhinoceros.

Figure 1
Numbered design steps / commands for phase 1-physical modelling iterations.



The students were asked to design a retail space of 150m2 using the Controlled Transformations method while manipulating / multiplying, an initial geometry of either a sphere or a control point curve, using solely the Rhinoceros software. All transformations were done by using some of the commands used in semester 1.

Students could again go back to any previous step, and iterate their design, resulting to different outcomes.This phase is using the same method of Phase 1; geometric transformations and mapping of the four design steps and instructions, but only using the Rhinoceros software.

Students could still sketch and make test physical models, but only of elements they initially designed in Rhino. This way, they had to adapt to the way the digital tool itself, the way the software, functions. And this is why the were introduced to this design thinking and the basic verb / commands in the previous semester, even when transforming physical models.

This was done in an effort to help students design a project that was not predefined in their sketchbooks, but was conceived and formed while using the software. The method is actually an effort to help students use form-finding software as a tool of architectural synthesis (Computation), instead of mere representation (Computerisation) as Terziids (2006) discusses.

It was important to have the same audience as Phase 1 (the same cohort of students) in order to test and evaluate their progression into Computational Design Thinking, based on the transition from physical, to digital modelling.

The students were introduced to basic digital modelling using the Rhinoceros software in the first two weeks of semester 2. This was achieved through two workshops with a duration of three hours each.

At the same time, in an effort to help students understand that digital design is closely related to CAM technologies, such as 3D printing and laser cutting, they were introduced to a now broadly used construction technique: the waffle.

This means they had to add a final design step, which was to digitally model a waffle version of their blob or curved surface(s). This is a quite simple and easy step in Rhino, which can be done by the contours command or by projecting lines on any geometry. This extra step was quite important, as a way to start thinking of the tectonics and actual fabrication of complex, digitally designed surfaces, that traditional construction techniques would be too expensive to use or too time-consuming.

This part of Phase 2 was crucial in this learning method, in order to help students reconnect the digital with the physical world (their digital designs to physical scale models).

The timeframe for Phase 2 was longer than Phase 1, in order to allow students to adjust to the Rhino software and fabrication tools. This is also why students only had one design workshop-project during this semester.

A series of digital models were produced throughout Phase 2 in semester 2, the same way diagrams and physical models where produced during Phase 1 in semester 1 (Figure 2).

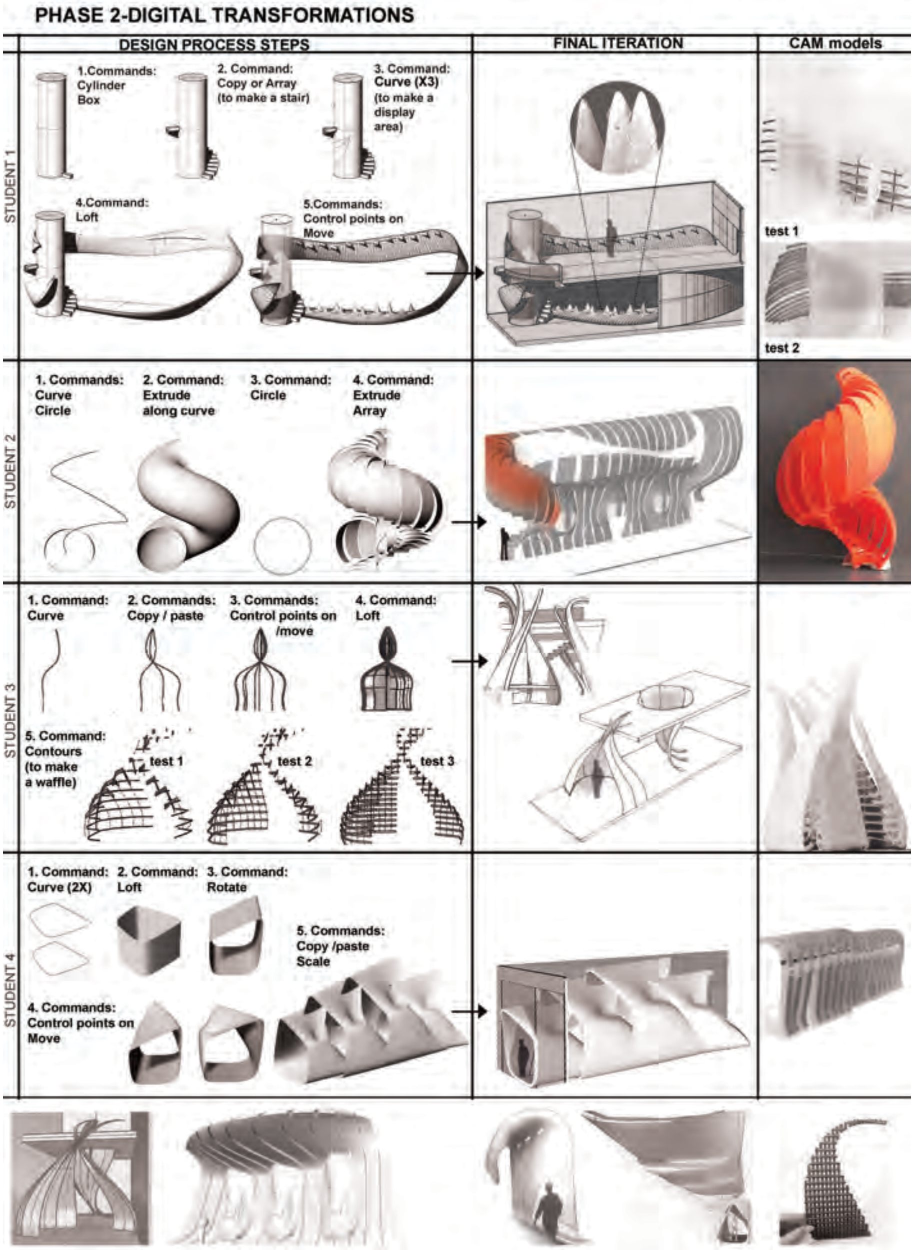
At the same time, physical model versions of the project iterations were materialized, as a way to test the design aesthetically and structurally, which then informed the design as feedback, creating further digital model iterations. The CAM methods that were introduced to the students over a three-hour session, included 3D printing and laser cutting. Laser cutting their iterations allowed students to manually assemble each of the waffle flat members.

EVALUATION

The way the proposed method is evaluated, is by comparing the cohort marks to those of previous years, comments by mark moderators and comments in the anonymous student survey.

Students managed to tackle the studio's design approach and requirements quite well, even though this was the first semester term of their studies. The student performance, Personal Development forms, anonymous survey and final marks (compared to the

Figure 2
Numbered design steps / commands for phase 2- digital modelling iterations.



previous years) indicate a positive outcome on the proposed design method.
It is noted that students had the same amount of tutoring and design studio contact hours, as our university has had for first-year students in previous years.Looking at the student marking statistics at the end of first year, the A marks did rise 50% compared to the previous year, due to the Controlled Transformations method. An anonymous student survey showed that 100% of the students found that these design studio workshops (combined with theory and precedents lectures) have improved their knowledge and understanding of the subject (Figure 3).

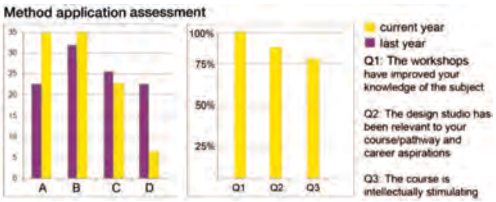


Figure 3 (Left): Marks comparison with last year. (Right): Student comments.

CONCLUSIONS
This method allows students to “manually” return to a previous step of the process and iterate their design, which would then result to different design outcomes, if the initial design steps - instructions - parameters are changed. During this process, each step - transformation instruction (and resulting changes on the form of the design) are documented with diagrams. The diagrams explain the instructions for each design step, either using physical or digital models. This test in first-year teaching of a design studio indicates how his method can subtly introduce students to Computational Design Thinking. And how digital design tools are actually changing the way we design architecture, even if we never choose to use any digital design tool, such as parametric software. It is a method that deserves to be investigated further.

ACKNOWLEDGEMENTS
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Conversations between architects and engineers

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The structural education in architectural schools emphasize that the dialogue between professionals is what should be raised as the point of connection between the conception of the structural morphology to be carried out by the architect and its validation and construction by the structural engineer. However, is this dialogue occurring? The proposal of this work is to study the conversational model proposed by Paul Pangaro (2009), based on Gordon Pask's Conversation Theory (1976a), and investigate if in fact a dialogic process between architectural design and structures education in architectural schools occurs, or if there exist the possibility of proposing a new conversational model, promoting transdisciplinary participation and collaboration procedures.Please write your abstract here by clicking this paragraph.

Keywords: *Architectural Design Teaching, Structural Education, Conversation Theory*

INTRODUCTION

Structural education is a key piece for that architectural students think about the relations between form, materiality and tectonics, since they aid in the reasoning of physical procedures for design, leading to a point of convergence between the disciplines of architectural design and structural engineering, whose lack of organicity only accentuates the fragmentation between design and construction. Structural education in architecture is not an end as in civil engineering courses that form professionals who develop structural calculations; should be a means for students to think about the tectonics of the form. The fragmentation between the disciplines of architectural design and structural engineering corroborates to an atectonic design thinking, favoring the simplistic application of technique and the generation of fashion images (FRAMPTON, 1995).

For decades, structural education in architectural schools has trained architects to the routine of structural engineers, in which there is no critical, reflexive and dialogical knowledge (SANTOS, KAPP, 2014). With disciplines focused mainly on quantitative aspects, they are too abstract, and do not offer to architectural student's adequate tools to appropriate itself to the relationship of material behavior to design a structural system. Thus, they fail to develop a structural reasoning from an analytical understanding of the various possible solutions to a design problem.

However, the teaching plans of structures disciplines offered in the architectural schools emphasize that the dialogue between professionals is what should be raised as the point of connection between the conception of the structural form to be carried out by the architect and its validation and construction by the structural engineer. But in teaching practice is this desirable dialogue between architectural design disciplines and structural education is effectively taking place?

To realize this analysis, we propose as methodology use the conversational model of Pangaro (2009) based on the concepts developed by Gordon Pask's Theory of Conversation (1976a). Thus, will be organized a conversational model adapted to analyze the relationship between architectural design teaching and structural education will be organized, in order to identify the existing problems in the current model. With this, it will be possible to propose a conversational model among these disciplines that effectively allows a dialogic practice of design, instrumenting the architects to elaborate new project systems that propitiate a practice of collective construction of knowledge through participatory and collaborative processes, in which architecture becomes a knowledge, not an autonomous discipline (MONTANER, 2017).

CONVERSATION THEORY

Conversational Theory was developed by Gordon Pask (1976a) and originated from a cybernetic assembly in which the fundamental idea is that learning occurs through conversations about the subject matter of the discipline, making knowledge explicit. Pask defines conversation as "an intersection between two second order systems in which humans, machines and environments may be engaged in collaborative information exchange." Second-order cybernetics applied to the design places it as a conversation in which participants must learn together. According to Pask (1980), the Theory of Conversation is used to illustrate an argument in favor of reflexive and relativistic theories in cybernetics and systems studies. Language in the Theory of Conversation is fundamental, in that through a means of processing, has as its property the ability to question, command, respond, obey and explain a certain goal.

Dubberly and Pangaro (2009) use Gordon Pask's cybernetic models of conversation theory because they are based on an in-depth study of the interaction between human-human and human-machine, in which it is believed that in conversation it is only possible to learn new concepts, share and evolve knowledge, and, confirm agreement. In conversation the output of one learning system becomes the input to another.

In conversation systems, based on cybernetic theory, humans, machines and environments can be engaged in collaborative information exchange. For Dubberly and Pangaro (2009), the conversation process occurs when its participants perform the following tasks:

1. Open a channel by sending an initial message of common interest;
2. Commit to engage with a symmetrical relationship between participants;
3. Construct meaning, in which the basis of the conversation must be the sharing of contexts, with common language and same social norms;
4. Evolve, since the conversation affects both participants, in which changes brought about by the conversations have lasting value;
5. Converge on agreement through common goals;
6. Act or transact, developing cooperative relationships;

The Conversion Theory applied to teaching practices requires that the methodology developed have a cyclicality that allows the student to reconstruct a concept and a consistency, allowing all the approached topics can be identified separately (PASK, 1976b), opening new processes of conversation. In the autonomous conversation model by Pangaro (2009), as shown in Figure 1, the Participant A is the one who initiates the process of collaboration through the conversation, defining the initial goals according to his point of view, articulating the logic of conducting the conversation considering that new goals or new opportunities can emerge during the process. The Participant A has access to a learning structure but is ignorant of some topics. The Participant B should have the answers to the questions of Participant A providing appropriated demonstrations (PASK, 1976b). The conversation begins only if one of the participants have a goal, specific or general, articulated or without form.

Thus, Pangaro (2009) systematizes what would be a conversational model and establishes some requirements for its organization:

1. Context: moment, situation, place and/or shared history;
2. Language: initial shared means for conveying meaning;
3. Agreement: shared understanding of concepts, intent, values that may lead to an action;
4. Exchange: availability for interaction, result of a shared language and a context conducive to interaction that can build an agreement;
5. Action or (Trans)action: cooperative conversation, circular and recursive.

ANALYSIS OF CURRENT TEACHING PRACTICE

In structures disciplines currently offered in architectural school , what exists is a technical communication. For Pask (apud PANGARO, 2017) the difference between communication and conversation is that for the dialogue to occur, something must be transformed for one or more participants, be it the understanding of the subject, concepts, intentions or values. If this transformation does not occur, what happened was a mere exchange of messages.

The current model of structural education is fragmented into disciplines that follow a similar civil engineering education, having disciplines of theoretical foundation (introduction to structural systems), intermediate knowledge (structural analysis and resistance of materials) and specific advanced knowledge (concrete, steel and wood). All disciplines have as bias the structural analysis by the analytical method, that is, using mathematical equations. Experimental methods, focused on the development of physical models, and computational methods that allow a better visualization of the physical behavior of the models are not used. In this way, students are only instrumented with an abstract mathematical language that is difficult to apply to architectural design. In this way, is the mathematical and abstract language used for teaching structures in architectural schools enough for the establishment of a conversational practice?

In architectural teaching, design disciplines wish to learn about structures for definitions of spatiality, morphology, and construction materiality. The role of teaching structures is a cooperative action with the dialogue to be established. Thus, in this dialogue, architectural design teaching is Participant A (which initiates the conversation with an action) and structural education is Participant B (which reacts to this action with a transaction).

The objective of this dialogue should be to provide the architect with structural knowledge that allows flexibility in structural parameters in harmony with spatial articulation. The structure in a tectonic design conception is not an autonomous object that must suit the space or vice versa. The architectural design teaching is (or should be) the driver of the conversation between agents, promoting the opening of common channels of conversation. In the current teaching model there is no formalized environment for the conversation with teaching of structures to take place.

In this way, we will first analyze current teaching practice through the bias of the conversational model, verifying if there is a conversation between architectural design teaching and structural education within the context of each discipline:

Participant A: Architectural Design Teaching

1. Context: architectural design disciplines;
2. Language: manual or digital representation methods of architectural design;
3. Agreement: launch of the structure according to pre-sizing criteria;

4. Exchange: when it occurs, happens through the analysis of examples and counter-examples of structural solutions of analogous works. It may also occur consulting the specific bibliography of structural knowledge directed to the learning of architects;
5. Action or (Trans)action: practically does not occur. It depends on the individual willingness of design teachers and students to seek some contact with the teachers of structures disciplines.

Participant B: Structural Education

1. Context: disciplines of structures;
2. Language: mathematics through analytical method;
3. Agreement: according to the subjects of disciplines, only the basic concepts of the contents are offered in such a way that the architects can carry out a structural pre-dimensioning and dialogue with structural engineers in professional practice;
4. Exchange: the inadequacy of the application of language to design development does not allow the exchange;
5. (Trans)action: practically nonexistent since the exchanges are made difficult by the language used;

In the current model, there is no possibility of feedback, and a process of linear causality is created. According to Dubberly and Pangaro (2015a), this linear process does not allow the iteration, which would be the correction of the error, and the convergence of objectives among the participating agents, limiting design to simplified feedbacks. In this way, for the proposition of a conversational model between the architectural design teaching and structural education, it is important that there is a context that allows the possibility of multiple feedbacks, promoting cir-

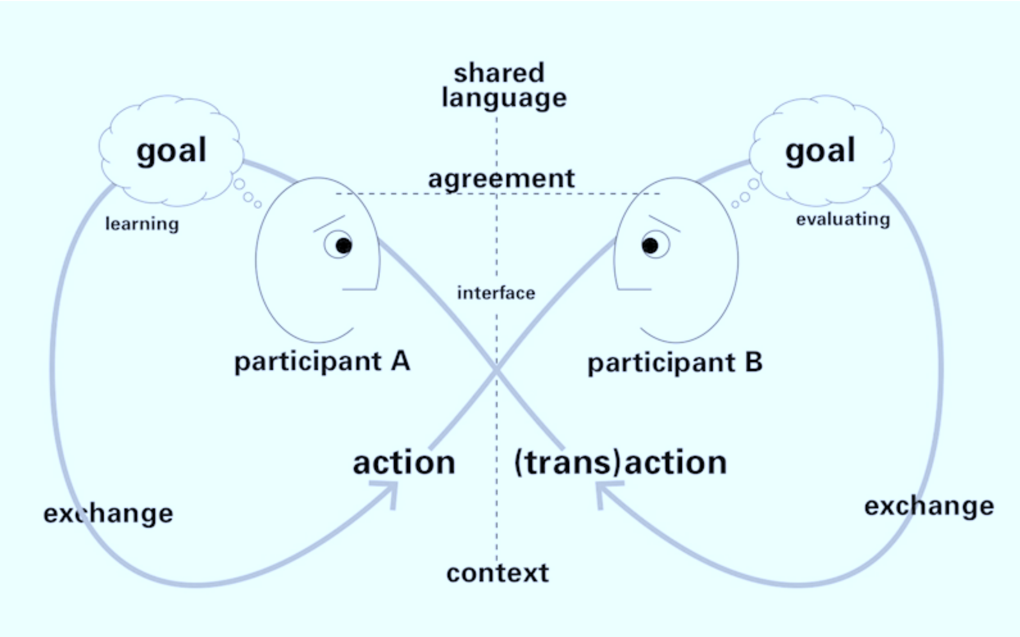

Figure 1
Simplified view of Pask's view of conversation. Pangaro, 2017.

cularity and recursion. For this, it is fundamental that the interaction of Participant B in the context of Participant A, developing a common language, with explicit objectives, in a context that facilitates the exchanges, in which these will serve as the basis for a joint action and for the creation of new values.

PROPOSAL OF A CONVERSATIONAL MODEL

Cybernetics studies how systems organize themselves, dealing with how they communicate internally and with other systems, which stimulates collaborative transdisciplinary thinking. For Von Foerster (apud DUBBERLY, PANGARO, 2015b, p.5), "one can and should try to communicate beyond the boundaries, and often the abysses, that separate the various sciences."

Some attempts to promote this integration have been developed to improve the dialogue between architectural design teaching and structural education. As can be seen in III Eneeea , some Brazilian universities focus on language change (experimental methods with the use of physical models or experiments in experimental beds), others involving new participants (engineering professors present in the design disciplines), or still, in the proposition of a new conversational model.

However, these propositions are focused on technical communication, not presenting more reflections regarding the changes of the architecture itself and its contemporary condition. For Montaner (2016), contemporary architecture has a contextualist and complex synthesis character, in which a new pragmatism is reformulated through practical tools of knowledge, analysis and design. According to him, the diagrammatic practices and the digital tools propitiate the development of an architectural theory related to an interactive pragmatism. Pangaro (2011) believes that design development should be more concerned with the design process than with the shape of objects, and that without the creation of a new language, innovation is limited to improvements in existing processes. But, how to develop a new language?

The proposal of a new conversational model between the architectural design teaching and structural education seeks to promote a common language among the participants, so that it is possible for the exchanges to be effectively carried out. For this, it is fundamental that Participant B promote its (trans) action within the same environment of design teaching (Participant A). Participant B can be machine (use of structural analysis software) or human (teacher of structures disciplines). In this way the proposed conversations are about promoting human-machine interaction, or human-machine-human interaction.

Conversation human-machine

In the first hypothesis, which we will call the Conversational Model Type 1 (focusing on human-machine conversation), the proposal is to develop a teaching model in which students use structural analysis software to develop performance-based design methodologies with focus in optimization, generation or computational form-finding) in the existing design disciplines. This model, as elucidated in Table 1, consists of involving Participant B in the conversation (structural analysis software) through human-machine interaction. This conversational model produces the following interactions:

In this model, Participant A are the architectural design teacher (A.1) and students (A.2), and Participant B is the structural analysis software (B.1). The design teacher establishes the dialogue with the software in two moments: in the first, in the selection and verification of the possibility of feedbacks according to the objective; and in the second, directing the students to interact with the software in the developed process. The conversation takes place between design teachers, students, and structural analysis software. The purpose of human-machine conversation is to broaden the possibilities for conversation.

Interaction with computers serves to cooperate in making decisions in complex situations. In advanced design environments, what for Oxman

	Participant A - action		Participant B – (trans) action
Conversation	**Human** (*A.1*)	**Human** (*A.2*)	**Machine** (*B.1*)
Human (*A.1*)	between architectural design teachers	students – architectural design teacher	*structural analysis software* – architectural design teachers
Human (*A.2*)	architectural design teacher - students	between students	*structural analysis software* - students
Machine (*B.1*)	architectural design teacher - *structural analysis software*	students - *structural analysis software*	Computacional iteraction

Table 1
Conversacional Model Type 1. Prepared by the author.

(2008) would be the performance-based design, using human-machine interaction and iteration between multiple agents, it is possible to create a conversation process with multiple feedbacks and recursion. This process would have the potential to transform the relationships between architects and engineers, where through a common language provided by the digital medium, values would be explicit and both would share the same goal.

Oxman (2012) defines performance as the ability to act directly on the physical properties of design and can be extended to include qualitative aspects as spatial factors in technical simulations. For Kolarevic (2005), the concept of performance goes far beyond aesthetic, functional and technical aspects, and can be extended to a financial, cultural, spatial and social dimension. The understanding of performance as a process demands a revision of the understanding of the "built body" as a "static body", suggesting the etymological idea of the formation of the architectural object through movement.

In addition to the dialogue between architectural design and structures, the performance-based digital design includes the computer as part of the process, a third participant involved in the conversation. Incorporating technology as a conversation interface tool provides participants with a shared language for a cooperative dialogic process, facilitating the development of an interactive, iterative, circular, and recursive process. For Oxman and Oxman (2010), the digital cooperative process dilutes the questions of authorship of form, through investigative and experimental processes, reversing the way of thinking form, force and structure.

In this way, based on the human-machine conversation applied to teaching, it was proposed the use of structural analysis software's in design disciplines. Thus, we have the following structure for the development of the Conversational Model Type1:

1. Context: architectural design disciplines;
2. Language: use of simplified structural analysis software for structural form-finding integrated to theoretical classes of material properties;
3. Agreement: learning of structural analysis software to aid in the preliminary structural sizing of the proposed structural typology;
4. Exchange: the software provides the preliminary structural sizing through the amount of material required;
5. Action or (Trans)action: recursion in the preliminary sizing and in the choice of materials during the development of the architectural design;

In this model, what is observed is that students who already have intermediate and advanced knowledge (both of design and structures) can engage in the conversation model. This is because they can understand the objectives, the proposed language and in this way use the software transaction for application in the design process. However, what is perceived in this model is that the simplification of the language used does not allow the engagement for recursion and the engagement with other conversations, being only an efficient tool for the students to explore the materiality of the object.

Conversation human-machine-human

In a second hypothesis for the construction of the model, due to its limitations identified in Type 1, the demands of knowledge extrapolate the human-machine conversation and it is necessary to include a new Participant B, who would be a structural engineering teacher. This can be introduced as a new element, extending the human-machine conversation to a human-machine-human conversation, opening new channels of conversations that need to be worked on. In this model, which will be identified as Conversational Model Type 2, several conversations can occur simultaneously as shown in Table 2, which would require that the design teacher explain to all participants the goal and values involved, with an agreement and an engagement of all in order to avoid noise, and consequently, conflicts of interest between the participants.

According to Pask (1980), a person can simultaneously have the perspective of more than one participant, unifying the internal conversation. When adopting different roles, this participant should consider the merits of the various hypotheses that may arise from the other participants. In this model the Participant A in the figure of the design teacher (A.1), would be the participant that performs this function. If there is no agreement and engagement with Participant B in the structural engineering teacher figure (B.2), the entire process may lead to a conflicting transaction, or even make it unfeasible. In this proposition, several conversations may occur:

The proposal to create the Conversational Model Type 2, considering all the complexity involved and the multiple interactions provided, is not to create a closed model, but to create a system with explicit subjectivities, values and responsibilities, allowing all participants to create. Conversation is necessary to converge on shared goals, and so reorder the situation in order to act together. In this way, the conversation between people is fundamental for understanding the principles of duality, complementarity and conservation. In this way, there can be no loss of concepts in the development of a single environment for the two disciplines (design and structures). For Pask (1980), the principle of conserving the information to be transferred in the conversation through language and means is what maintains the coherence of the system. In this way, the proposition of a Conversational Model Type 2 for the synthesis of all conversations that would occur internally, encompasses the following definitions:

1. Context: hybrid disciplines of architectural and structural design;
2. Language: learning of structural analysis software integrated to theoretical classes of structural design in its quantitative and qualitative dimensions;
3. Agreement: learning of concepts and application in the software for iteration with the computational model;
4. Exchange: development of an iterative process in which the participants have the software evaluations as interface for the dialogue;
5. Action or (Trans)action: recursion in the development of architectural design. The participation of the structural engineering teacher is required for the sophistication of the iteration. Architects and engineers develop a collaborative relationship;

In order to promote a circular and recursive process in a complex model like Type 2, the pedagogical structure of the proposed disciplines can be divided into four moments based on Pangaro (2011), being all it-

	***Participant A** - action*		***Participant B** – (trans) action*	
Conversation	**Human** (*A.1*)	**Human** (*A.2*)	**Machine** (*B.1*)	**Human** (*B.2*)
Human (*A.1*)	between architectural design teachers	students – architectural design teacher	*structural analysis software* – architectural design teachers	structural engineering teacher– architectural design teachers
Human (*A.2*)	architectural design teacher - students	between students	*structural analysis software* - students	structural engineering teacher– students
Machine (*B.1*)	architectural design teacher - *structural analysis software*	students - *structural analysis software*	computacional iteraction	structural engineering teachers - *structural analysis software*
Human (*B.2*)	architectural design teacher – structural engineering teachers	students – structural engineering teachers	validation of results	conversation between structural engineering teachers

Table 2 Conversational Model Type 2. Prepared by the author.

erative and recursive:

A. Conversation to Agree on Goals: moment that the objectives must be explained and agreed upon until they are brought to engagement;

B. Conversation to Design the Designing: moment of identification of irreplaceable knowledge for the design of a new space of possibilities;

C. Conversation to Create New Language: as a new space of possibilities evolves, a new language is shaped and defined;

D. Conversation to Agree on Means: agreement on the action plan for the development of products using the proposed conversational model.

Hybrid disciplines have as a proposal to open dialogues, not eliminating the possibility of maintaining the current disciplines of structures, on the contrary, stimulate students to look for these theoretical tools to better understand how to use the resources of analysis and iteration provided by structural analysis software's. The software visual resources allow the visualization of the behavior of the structures, leading to a recognition of the concepts learned through analytical mathematical models, which, because they are too abstract, are generally not well understood.

What was noticed in the development of Conversational Model Type 2 is that the difference between students with basic knowledge of structures and students with intermediate and advanced knowledge is not perceived, being that all engage in the development of the iterative process and require the participation of a structural engineering teacher in the process. This conversation can even extrapolate the edges of the discipline itself, enabling and encouraging students to seek new knowledge with other structural engineering teachers or even with other construction workers (designers, industry and construction workers).

Students with advanced knowledge of both design and structures, engage in dialogue that overflows the discipline. These students seek the theoretical knowledge offered in the traditional disciplines of structures (some return to attend classes in disciplines such as resistance of materials and structural analysis), seek dialogue with other structural engineer teachers, seek other structural analysis software's, other professionals in the field and even engage in a critical dialogue with the construction industry.

CONCLUSION

The modern division of labor has led architects and engineers to develop a collaborative relationship through help or support. That is, the architect develops a project and the engineer helps or assists him with his work, not acting jointly in his development. The change of relationship in the sense of developing a cooperative work redefines the positions of professionals and re-approximate the work of both, where the action takes place jointly for the same purpose.

The pedagogical proposal to develop conversational models for teaching design and structures goes through what Montaner (2017) purposes for a practice towards an architecture of action. For Dubberly and Pangaro (2015a), the conversation for action promotes an ethical (in agreement with goals), cooperative (in agreement with means), innovative (creating a new language) and responsible (creating a new process).

According to Dubberly and Pangaro (2015a), knowledge of vocabulary and grammar is not a prerequisite but provides a more fertile ground for the emergence of poetry, and of delight. By designing interactive environments as computational extensions of human agency or new social discourses to govern social change, second-order design facilitates the emergence of conditions in which others can design, creating conditions in which conversations can emerge, thereby increasing the number of options open to all.

In order for structural education to be part of a conversation within the design disciplines, it is necessary that the architectural design teaching is also open to substitution of a typological model, with a correctness of the linear form, for a topological performance model, in which the architect does not have control of the designed object, but rather of the process, allowing architecture to emerge from participation and emergence between a variety of agents. The digital tools of structural analysis provide a set of iterativity between the parameters used to conceive the space and its possibilities of materialization through processes of optimization, generation or a structural form-finding. In this case, the computer acts as a cybernetic instrument that responds to the parameters established by the students for the design of the structural system instructing and being instructed by it, in a recursive process that can add as many agents as necessary. In this process unexpected results can emerge, not foreseen initially, creating novelty for both participants.

The creation of collaborative design processes in which knowledge is built collectively through the participation of other agents leads to a paradigm shift. Established conversations can transform individuals and organizations by changing values and modes of arrangement, and conversation initiated in teaching can be replicated in professional practice. For Pangaro (2017), when a conversation begins, it never ends. In this way, we believe that the conversation initiated in the teaching environment has the capacity to transform professional practice, thus modifying the relationships between civil construction agents (architects, engineers, workers and users) and their forms of participation through the emergence of dialogical practices, in which the discussion is oriented by the object that connects them or can connect.

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Evaluation of systems for video-based online teaching

Create your own MOOC or SPOC

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There are a lot of discussions about digitalizing university teaching and opening it to civil society. In this context, we investigate the current options for setting up and distributing video-based online courses. First, we make a review of a subjectively selected set of existing platforms and technologies for video-based online courses. Next, we discuss the needs of futures online teaching concepts and the corresponding challenges of digitalization for university teaching. We summarize essential aspects of the considered platforms, technologies, and today's examples in tables. The main result is an overview of systems that can be used to start your online teaching initiative with a small budget.

Keywords: *Online learning, video-based courses, MOOC, SPOC*

INTRODUCTION

During the last years, online learning platforms like Coursera, FutureLearn or edX successfully established an extension of the university education and opened high quality massive open online courses (MOOC) to everyone with an internet connection. These platforms offer courses from the best universities worldwide freely accessible. This development can be considered as a democratization of the elite university sector. The main differences between the traditional university education and the online teaching platforms are the physical locations where you study and the degree you receive. Whereas, for the latter, there are first steps offering degrees from universities that you can earn primarily via online courses, though these degrees are not available for free anymore.

Consequently, the new platforms compete directly with the traditional education system. There is a trend that you can study many programs from the best universities without leaving your desk. This development raises questions about the future of traditional universities: Is there a unique selling point of the traditional institution of a university? What role does the historical place of a university play? What values have social interaction between students and with the teachers?

Currently, we find the big players on the leading platforms primarily, since they can afford the joining fee, the investments in the development of new online courses, and the corresponding infrastructure [1]. Smaller and hardly known universities have no access to these platforms, which shed a different light on the idea of democratizing education. Furthermore, the platform economy that controls the content reinforces the dominance of the top global uni-

versities. This development is logical since the attractivity, and economic success of the platforms go hand in hand with offering high-quality content ensured by the reputation of the universities.
If location and spatial boundaries are no limiting factors anymore, the winnings of the big players continue to rise, whereas the visibility of other universities decreases.

The question motivates this article, how especially smaller and less known universities may react to the rapid digitalization of the education system. How can universities transform and open themselves by their digital offers and by new forms of cooperation between each other? There are huge potentials in the public universities for creating a counterweight to the huge platforms to avoid the dominance of private companies that controls access and content. Important conditions for a bottom-up driven digital transformation of universities is the available technology and technical infrastructure.

Of cause, the educational concepts need to be adapted for MOOCs (Fernández-díaz et al., 2017). In the context of an architectural program, Stellingwerff et al. (2018) described how online design education experience could be improved by using the tools provided by edX. Spyropoulou et al. (2015) reported on their results, developing a computer programming MOOC. In contrast to these descriptions of pedagogic concepts, we evaluate available systems for online teaching concerning their functionality, flexibility, and costs. We compare not all available systems but some that we considered as the most important respectively reasonable ones for our intentions.

As a result, we describe the advantages and disadvantages of the compared systems. The comparison is not very systematic because the considered systems are made for different purposes, including various possibilities and foci so that we have to compare apples with oranges partially.
Nevertheless, we offer a useful insight into the system you should use with a given budget to start your online teaching initiative. We focus on video-based learning methods for lectures, technical introductions, or tutorials that are accompanied by texts, quizzes, assignments, discussion forums, online apps, webinars, teacher-student communication, and social media chat rooms and groups.

EVALUATED SYSTEMS AND PLATFORMS

In the following, we consider some systems and platforms for video-based online teaching in more detail. Table 1 gives an overview of the main aspects of the compared technologies.

MOOC platforms

One of the obvious ways to start with offering your online video course is to join an existing MOOC platform. The advantage of such platforms is that they take care of the technical infrastructure and member management etc. You primarily need to provide the content. We contacted Coursera, FutureLearn, and edX if they would accept courses from us. We are lecturers at a smaller German University with a good international reputation. Unfortunately, only FutureLearn answered to our request. FutureLearn as the others have a partner program, which states the requirements for a partner institution. In the case of FutureLearn these are basically:

- Demonstrable expertise in an area of knowledge
- Strong academic research
- A commitment to advancing education

Other platforms like Coursera or edX have similar regulations for their partner programs. The listed criteria are reasonable for a quality assessment of a partner institution.
However, if you would like to start with a small initiative and your university is not already a partner with one of the platforms, it would require a lot of administration effort and time to become a partner, even if your institution fulfills the high demands for these criteria. To avoid these barriers, you may use a platform with lower quality content where everyone can contribute or set up your platform.

In the following, we concentrate on the possibilities and systems for setting up our teaching platform.

Advantages: You can reach a huge number of potential users with a MOOC. It is possible to collaborate with other universities for combining courses for special certificates.

Disadvantage: It is difficult to create courses that you can use as MOOC and for the students of a university in the context of a seminar. Not least, the European data protection law does not allow forcing students of your university to subscribe at a commercial MOOC platform. Therefore, the MOOC activities are separated from the traditional teaching activities at the university.

Moodle

Latest at this point, you may look at the teaching platform that your university is already using. At least in Europe, most universities have their own internally digital teaching support system. In many cases that we know of (TU Munich, ETH Zurich, Bauhaus-University Weimar, TU Vienna), Moodle is used. Moodle is an excellent system for providing digital materials for courses for managing students' submissions, grades, and communication. Usually, it is used for Small Private Online Course (SPOC).

Advantage: Moodle is open source and can be integrated very well to existing processes and legal frameworks of universities. Furthermore, it is very actively developed, and many universities invest money for developing additional modules or plugins.

Disadvantage: Moodle is relatively closed for users external to universities, and it does not provide functions to create course collection websites like the MOOCs platform show it. In our test, it was also challenging to create a good user interface for a sequence of video lectures organized in weekly modules. Also, we experienced performance issues with Moodle when loading many videos for a course, but this may be an individual technical problem that was not further investigated. The costs of Moodle depend mainly on the number of students that use the system. Either you host it yourself, or you use a basic hosting plan.

Open edX

Another option is to use Open edX, which is the open source MOOC platform developed for edX.org courses. It provides the functions that are included for courses on edX.org, but the courses are not linked with the main edx.org platform. Therefore, you need a hosting service for Open edX, which is technically relatively demanding. There are hosting services who manage the technical aspects, which starts in a basic version from 600 Euro per year but can become very expensive if you need more functionalities, students' access, or visual customization options.

Advantage: In case you use a hosting service, it works out of the box. You have the same features as courses on edX.

Disadvantage: Even if you manage to host it yourself, open EdX is too complicated that it can hardly be customized.

WordPress based Learning Management Systems

An alternative that is used by many smaller online teaching initiatives is to use the Content Management System (CMS) WordPress with plugins that extend it to a full Learning Management System (LMS). This option has the advantage that you can control many aspects of your online video teaching platform in detail. You need a web server provided by the university to host WordPress, but the installation is not very difficult. More difficult is to choose one of the available LMS plugins. We considered LearnPress and LearnDash. Many websites compare the systems, but they are either not very detailed or influenced by some companies that want to promote their products. We tested in detail the open source LearnPress and the proprietary LearnDash.

Advantage: The combination of WordPress and an LMS offers a very flexible way to combine the enormous number of plugins from the WordPress universe and the ones of the LMS. This flexibility results in a platform that is customizable to nearly any use case without advanced technical skills. The costs for hosting and the software licenses are the cheapest of all the considered options.

	Accessibility	Technical requirements	Flexibility	Price	Privacy
MOOC platforms (*Coursera, edX, FutureLearn*)	- Free for all	- No technical requirements are needed	- Only for MOOCs, no SPOCs are possible - The layout and course structure cannot be changed	- High fee to become a partner university - Free for students - University dependent fee for an official graduation	Coursera, edX, and FutureLearn are commercial platforms. The first both are based in the USA, the latter in the UK. Storing private student data at these platforms is not allowed under European law
Open edX	- Can be controlled individually	- If you use a hosting service, no technical requirements are needed - If you host it yourself, the technical requirements are very demanding	- Suitable for MOOCs and SPOCs - Only the customization offered by the host is possible	- Open Source - Hosting costs can become high - Student fees can be defined individually	Usually hosted by non-university services. Storing private student data at host outside the country of the university is difficult, but possible depending on the location of the hosting service
Moodle	- Usually only for university members (if hosted by the university)	- Usually hosted by the university or a hosting service. We have not found an example for a self-hosted solution	- Very flexible for using it as accompanying tool for face-to-face seminars - Difficult to customize it for video-based online courses	- Open Source - Hosting plan starting from 250$ per year	Usually hosted by universities; therefore, privacy is not an issue. Using a hosting service may require special contracts
LearnPress (WordPress)	- Can be controlled individually	- Requires a self-hosted WordPress installation - Looks Great Out Of The Box	- Can be used for many different scenarios - There are a lot of additional plugins - Very well suited for video-based online courses	- Wordpress is free - Hosting costs - LearnPress: Free to $249 /per year	Can easily be hosted by universities; therefore, privacy is not an issue. Using a hosting service may require special contracts
LearnDash (WordPress)	- Can be controlled individually	- Requires a self-hosted WordPress installation - Needs some time to get used to the system and set up a beautiful online course website	- Can be used for many different scenarios - There are a lot of additional plugins, but they can increase the costs substantially - Very well suited for video-based online courses	- Wordpress is free - Hosting costs - LearnDash Cost: $159 - $189 /per year	Can easily be hosted by universities; therefore, privacy is not an issue. Using a hosting service may require special contracts

Table 1 Comparison of systems and platforms for video-based online teaching.

Disadvantage: The flexibility of the WordPress-LMS results in some training time to get used to the backend functions and the visual customization options of a course website. The maintenance of the platform needs some resources.

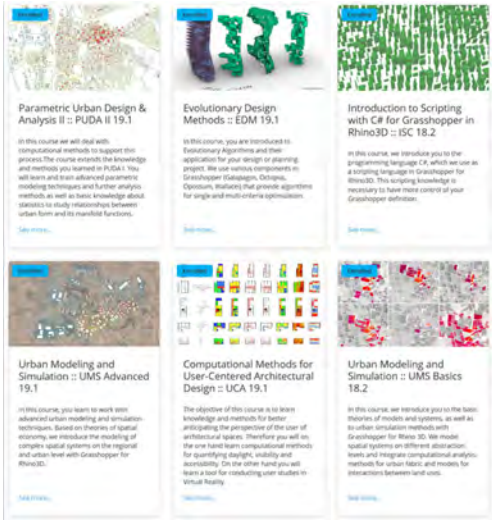

Figure 1
Courses at the Open Teaching Platform OTP at the Bauhaus-University Weimar.

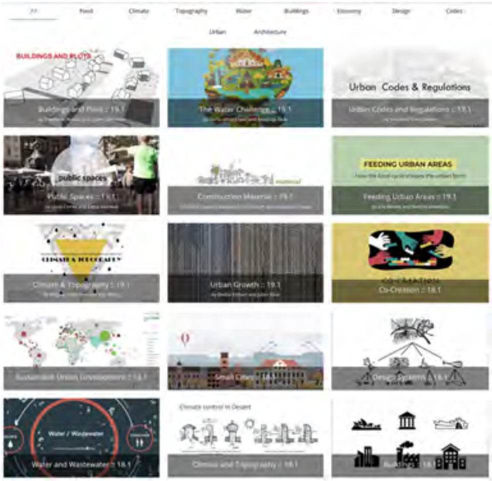

Figure 2
Results showing some students presentation on the OTP of the Bauhaus-University Weimar. Most presentations are linked to VideoAnt [4], where the time-based annotations are included.

OPEN UNIVERSITY CONCEPT

In this section, we present some conceptual ideas for a modern open online university. Open means in our context, that courses are accessible fur the public online without restrictions. Thus, we distinguish in the following between internal and external students. Internal are students that are inscribed at a university and external are all other participants that participate at a course for either free or a fee.

From our experience in developing our video-based Open Teaching Platform OTP at the Bauhaus-University Weimar (see Figure 1)[2] , one of the challenges is how to open courses flexibly for external students based on our teaching activities at the university. The video lectures can be used for internal and external purposes, whereas the requirements to the internal students were higher. Thus, we included assignments for evaluating internal students in detail, which is not possible for a wider external audience. Furthermore, we offer regular face-to-face meetings for discussing the corresponding tasks and individual questions and projects. On the other side, we need to automatize the progress of external students as much as possible. Therefore, smart usage of quizzes with a set of randomly selected question is a good approach. The quizzes can also be linked to tasks that require the usage of defined CAAD software.

It is an open question, how to combine internal and external students. Do they take the same courses or is a separation needed? These questions need to be also reflected from a legal perspective concerning data protection rights of internal students. For example, using the real name of a student at an open teaching platform is not self-evident.

Of cause, video-based online teaching requires the development of new teaching forms. We ask our students to submit their lectures in the form of videos and offer other types of student-submitted content (see Figure 2)[3]. We made excellent experiences with the technique of video annotations, as it is offered by VideoAnt [4]. It allows adding time-based comments to video lectures by students, which creates an exciting discussion dynamic. Such an approach can include contributions from internal and external students. Finally, it is an interesting method to accumulate and document research and design projects from the students systematically over many semesters, from which new students can learn.

After the first semester in which we used the new video-based online teaching method at the Bauhaus-University Weimar, we evaluated the experiences of the students. Their feedback was throughout positive, as the following comments show exemplary:

- *"everything was online, easy to follow on my own pace to learn deep topic"*
- *"keep up the high academic level of the learning platform"*
- *"communication; new topic to me; very international; very encouraging lectures"*

Online teaching offers various ways for student-student and teacher-student communication via emails, direct messages, announcements, forums, or social media frameworks. It is a meaningful approach to organize students into different groups for external and internal students to have separate communication channels, especially for information to and between internal students.

Lastly, the Holy Grail of open online teaching is the exchange of courses between universities. Theoretically, this should be possible in Europe based on the European Credit Transfer and Accumulation System (ECTS). ECTS is a credit system designed to make it easier for students to move between different countries as defined in the Bologna Process [5]. Nevertheless, the courses from other universities are not always compatible with local study plans. Thus, the practical implementation requires active and creative participation of the faculties and universities, leaving more flexibility to the students in defining their study plans.

EXAMPLES OF TODAY'S SYSTEMS

Beside the MOOC platforms introduced above, there are other examples of more or less open learning concepts that we consider in the following and summarize in Table 2:

One of the oldest alternatives to traditional universities is so-called Distance-Learning Universities. Some examples are the Fernuniversität Hagen in Germany [6], the FernUni Schweiz [7], or the Open University in England [8]. The main idea of these institutes is to offer to study while in employment. Professional schools at some universities also offer such concepts. Either the offering institutions use the classical form of sending paper-based study material by mail, or they use Moodle for distributing the content digitally and providing a more flexible digital communication channel with the lecturers.

A more restricted approach is to open courses for students already inscribed at a university. We can find such a SPOC concept at ETH Zurich, which use the term TORQUEs for Tiny, Open-with-Restrictions courses focused on QUality and Effectiveness. TORQUEs use Moodle for video-based courses, which are closely aligned with their face-to-face equivalents [9].

Combining content from universities in the federal state Hamburg, the Hamburg Open Online University HOOU was founded [10] with the goal of digitalizing science teaching and opening it to civil society. However, HOOU is not primarily a video-based teaching platform but provides various educational materials in the form of Open Educational Resources (OER), which may include video courses.

In contrast, to open teaching initiatives, there are commercial platforms that offer courses as paid service for an experienced professional who wants to learn a new skill. For the architecture, engineering & construction industry, there are, for example, ArchiStar Academy, ThinkParametric, and Performance Network that were founded in recent years. They offer tutorials primarily for software training and examples of projects implemented by a set of software tools.

Another alternative to offer video recordings of

Table 2
Provider of open learning concepts.

	Accessibility	Technology	Flexibility	Costs	Privacy
Fernuniversität Hagen	National university admission and course dependent requirements	Paper-based plus Moodle	Traditional paper/mail-based system; potentials of digital online teaching are not fully used	Fee depends on the study program	According to German privacy law
FernUni Schweiz	National university admission and course dependent requirements	Moodle	Well suited for SPOCs and internal users. Difficult for open formats	Fee depends on the study program	According to Swiss privacy law
Open University	Course dependent requirements	Moodle	Well suited for SPOCs and internal users. Difficult for open formats	Fee depends on the study program	According to UK privacy law
Studying at universities while in employment	National university admission and course dependent requirements	Depends on the university, but often it is Moodle	University-specific. Usually well suited for SPOCs and internal users.	Fee depends on the study program	according to privacy law of the university's country
TORQUEs ETH Zurich	Only for members of a Swiss university	Moodle	Well suited for SPOCs and internal users. Difficult for open formats	Inscription fee for a Swiss university	According to Swiss privacy law
HOOU	No restrictions	Self-developed system	Seems to be very flexible, integrating various web technologies	Free for all	According to German privacy law
OTP	Open courses without restrictions; For internal courses, the rules of the university apply	WordPress with LearnDash	Very flexible since based on WordPress, various plugins can be combined for individual purposes	Free for some courses. Costs depend on the course and certificate or graduation.	According to German privacy law
ArchiStar Academy	No restrictions	Not known	Not known; Made for architecture, engineering & construction industry	Free for essentials, EUR 570/year for full access	Commercial provider, the national law of the providers country apply
ThinkParametric	No restrictions	Not known	Not known; Made for architecture, engineering & construction industry	Membership $19/month or $228/year	Commercial provider, the national law of the providers country apply
Performance Network	No restrictions	Not known	Not known; Made for architecture, engineering & construction industry	For all courses on the platform: $197/month $1,997/year	Commercial provider, the national law of the providers country apply

courses is using YouTube or Vimeo channels. They are straightforward to handle and efficient for video distribution. There are good examples of CAAD channels [11], creative computer programming [12], or research methods [13].
However, by using such video channels, one is restricted primarily to the provision of videos. There are not many possibilities for communicating with students, adding tests, or managing inscriptions. Thus, we consider it not as a feasible option for video-based courses.

CONCLUSION

Our conclusion from the compared systems is that you need a customized website for a complete online video course. Therefore, Moodle would not be our first choice because the course structure is not ideal for a video-based online course, and we missed some functionalities to open and visually present courses. Open edX is an exciting alternative, but there are not many hosting services in Europe (which is essential concerning data protection regulations). From our perspective, the option to set up an online video course platform using WordPress extended by an LMS such as LearnDash or LearnPress is the most attractive one in terms of its flexibility but requires some technical competences.

From our experience, the most challenging aspect besides choosing the right platform is the creation of appropriate content. The new technologies allow numerous pedagogic experiments, which go far beyond just digitalizing the existing course materials. After our first semester, we changed our perspective on teaching entirely.

The development of MOOC and SPOC course formats allow an exchange of courses between universities. To a certain degree, students should be allowed to include courses from other universities in their programs, which could lead to entirely new programs across universities, where student exchange could be physical and virtual.

A remaining challenge is how universities provide sufficient resources for open online courses. The requirements for lifelong learning in modern societies require new teaching concepts and online teaching formats that shall not be limited by national borders.

ACKNOWLEDGMENT

On the accompanying post on the website [17] we provide further information on the described platforms and systems for video-based online teaching.

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Digital Empowerment for the “Experimental Bureau”

Work Based Learning in Architectural Education

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This paper describes the concept of the ``Experimental Bureau'' as a didactic environment aiming to deal with real-life design tasks within the framework of architectural education. Its main focus lies on the specific opportunities for digital empowerment of students who learn about the design process - sometimes even in the role of contractors - in real-life oriented project work. Thus the following questions come under scrutiny and discussion from an angle of work based learning: What kind of design problems are tackled in a meaningful way by students through the utilization of a digital strategy? What kind of software (or software mix) is chosen and what problems are addressed by the choice and handling of these digital tools? These questions are answered in a different way applying the format of the Experimental Bureau, driven by its real-life projects and client communication, in comparison to largely artificial tasks confined to the academic realm.

Keywords: *design education, real-life case study, stakeholder communication, real-world experience, didactic approach*

1 INTRODUCTION

One of the central issues of architectural education in an academic setting is its artificiality on one side and separation towards real-life conditions on the other side. Students usually work on design exercises in a rather controlled environment, receiving feedback from the academic staff. They have to trust their supervisors/tutors/teachers, who will specious supply them with second hand experience, especially in regards to the virtual demands and needs of clients. Since the translation of these requirements into spatial concepts and subsequent architectural solutions is one of the main traits of the architects work a certain degree of contact between students and clients/stakeholders deems more than desirable as part of the curriculum in design education. The term “didactic laboratory”, although it has been used with different connotations (see e.g. Amirante et al., p. 14), suits the concept of the Experimental Bureau.

In this paper, selected case studies from two different educational sites are presented and expounded, i.e. HafenCity University Hamburg and Technische Universität Wien. Both sites are carrying out design studio assignments nonetheless with a different scope and setting. The main focus of is the the elaboration of “digital empowerment”- in other words, how do students develop their skills to act with an increased ability to steer the design process.

2 THE DIDACTIC LAB ENVIRONMENT

This paper explores the concept of the Experimental Bureau as a didactic approach within the educational settings of a design studio. The format of the working context can be described as follows: Students are learning while working on a real-life architectural design project with actual/tangible principals in a process moderated by a professional architect and/or academic staff. In this regard the term "experiment" requires further elaboration in an academic context.

Experiment as a term is hinting at the secure perimeter surrounding e.g. an individual, the Greek "peri" translating as "around", while suggesting a leave of this secure perimeter. This necessarily contains the element of risk, which can be derived from the Greek "rhizikon" that among other translations has means "cliff". The cliff in this context signifies taking the risk as a step towards daring to leave secured perimeters (on risk and daring see e.g. Hahn 1958 and Röhrs 1966), heading into the unknown. Topographically it may also be the separation between land and water. To move safely in water cannot be learned fully on land. These reflections may be transferred into architectural and design education as the didactic format of the Experimental Bureau.

2.1 Exercise and Experiment

One significant difference between a design exercise within a protected context and an experiment within a controlled environment, is the element of risk. Safeguarding is more extensive if one declares a number of performed tasks an exercise, making the process the prime objective, aimed at the one completing the task and not so much at the outcome. An experiment is primarily concerned with an outcome which is beforehand unknown, the setup is conceived to contain and control possible risks, which, due to the very nature of true experiments, cannot be as safely limited as during an exercise. The predominant risk in the case of the experimental bureau in architectural education is the professional exposure, which is reduced again to a certain degree by academic supervision within the accompanying design studio.

2.2 Taking the Experimental Risk

Felix von Cube has discussed the relationship between risk and security in his publication "Gefährliche Sicherheit" (dangerous security) and pointed out, that human beings strive for both. The learner is intrigued by situations he/she cannot yet fully control, there is an attraction at least to a certain amount of risk. There is an intrinsic notion to turn this risk into security, to gain control over the situation (see von Cube 1990, p. 26 and Warwitz 2016). The Experimental Bureau attempts to use this mechanism among others to trigger an intrinsic student choice of digital strategies by enhancing motivational risk through real-life tasks.

Return of investment is, however, a risk factor for an involved professional architect while supervising students e.g. at the HafenCity University to work on an authentic project situation. Integrating students in a real-life design task may result in time losses, e.g. through essential educational processes and problem/solution discussions. On the other hand there is the possible gain of valuable future employees, the acquisition of a contract through academia and the prospect of dedicated project presentations in the media. On top of this, the issue of competition between work based learning and professional architects needs to be addressed by way of a win-win-strategy. This applies also to the working context of Technische Universität Wien, where (local) stakeholders, such as municipal/communal mayors, councilors, merchants etc. input an investment of time. During the intermediate and final critics the panel may be expanded with professional architects and governing officials. A participation of 20+ students delivers an adequate bandwidth of solutions. Furthermore, the exchange of views and opinions in a public context has proven to be fruitful.

When taking a closer look at digital strategies as part of the design process several lines of implementation can be identified. First of all a noticeable enhancement of a (classical) one-man/woman-setting needs to be mentioned. The power of computing allows to expand the "productivity" of a single person, for example by way of the generation of alternative design solutions. However, individual design work takes places within the setting of a larger studio group. Collaborative activities can and will be set out by way of common access to data and the creation thereof. The issue of subsequent sharing is especially important regarding the representation of the surroundings of a building plot given. A survey of the existing location/situation will most likely make use of digital data and is linked to the creation of a 3D-model of the surrounding context along with existing building structures. It may eventually lead to the delivery of a digitally fabricated physical model, where the participants in the design studio can insert a partial model of their design. The central availability of low threshold tools - such as laser-cutters - is around nowadays at most university locations and their handling is manageable. Although working in a scale (i.e. not 1:1) the relationship between "designing" and "making" receives upwind. Overall, the exchange with a larger group of studio members can work out fruitful and be expected to raise further development on the individual design work.

On top of this, the communication takes place by way of imagery, created by the students themselves, along with transformations of for example analogue drawing entities superimposed by digital sketching and eventually further manipulation.

3 CASE STUDIES IN AN EXPERIMENTAL CONTEXT

By using test cases a collection of digital necessities as a basis for this didactic format is gathered and discussed. The design programs stem from two different universities. Although different framework conditions are given, a number of communalities can readily be identified.

3.1 University Location A-HafenCity University Hamburg (HCU)

Since 2009 student competitions have been deployed by Kulcke et al. to integrate external partners into design-studio work. Especially impromptu design tasks, where students have to come almost ad hoc to solutions to be presented within the timeframe of two weeks in front of the jury, have been utilized for this strategy. The external partners e.g. companies, institution, NGOs and others are invited to take part in the task development, feedback sessions and most importantly in the final jury. And they supply the need, their real-life task.

Over the last ten years about 70 of these competitions have been organized this way at the HCU and the demand for a follow-up program has grown over the years. This demand is not only driven by students who took part in the competitions, but especially by the external partners. In the first case, which also involved the Hamburg University of Technology (TUHH) a follow-up project has lead to the realization of an interior design by two students (TUHH) at the International Building Exhibition (IBA) in Hamburg Wilhelmsburg in 2013 (fig. 1). The development of the didactic format of the Experimental Bureau stems from this demand and the experience gathered with such follow-up projects.

Figure 1
Students Philipp Popp and Ingo Höfert standing in front of their IBA interior design

A student competition from the same year was related to the "Rathauspassage". This second case study proved that the format of the Experimental Bureau can significantly contribute to public relations strategies of the academic institution in charge. The students' rendering was in the end decisive for the editor to publish the concept in an extended article of the main city newspaper Hamburger Abendblatt (fig. 2).


HAMBURG

Die Rathauspassage soll ans Licht kommen

Figure 2
Article on the project "Rathauspassage" in Hamburger Abendblatt 13.06.2013, rendering by Oskar Görg and Ferdinand Leser

In the third test case "BHH Sozialkontor", the student-driven choice of digital strategies within the real-life task of designing the entrance area of a psycho-physical therapy facility has been even more consciously integrated into the didactic approach.

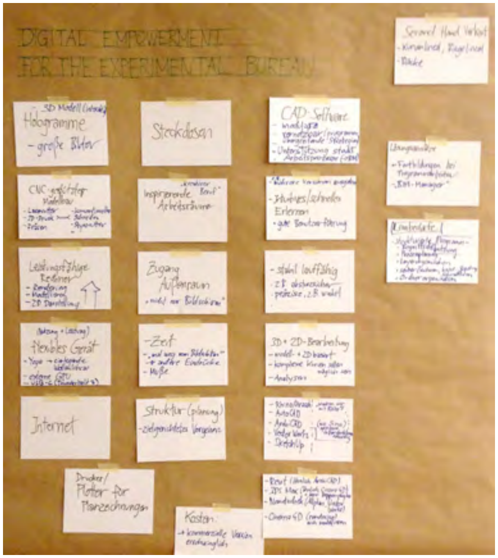

Figure 3
Collection of aspects as a result of a group discussion on digital necessities, students: Sandra Luu and Tom Ehlers

In this case the choice primarily concerned the digital collaborative workflow and the use of computer-aided parametric design.

At first data to discuss the use of digital tools in this didactic strategy has been generated within the format of a moderated group discussion with the two participants of the initial launch of the Experimental Bureau, explicitly labeled as such, as a didactic format with a focus on digital tools (fig. 3).

The group discussion consisted of several parts. In a starting session, the students were asked at first, what kind of digital support and tools seemed necessary for them to work in a conceptual environment like the experimental bureau. The second part of the starting session focused specifically on software issues. The students mentioned several CAD software solutions known to them through their curriculum and their work experience so far, while comparing traits that mattered to them and their work in general.

For projects worked on in this format it is vital that they are conducted in a real environment and with a real contract, only in this way the necessary sense of risk can be established, which supplies the format with its experimental character.

Regarding the implementation of digital strategies student versions for CAD software are in certain cases out of the question, since the software is commercially used. This applied e.g. to the project "BHH Sozialkontor". On the other hand the projects are small scale, among other reasons so as not to go into competition with professional bureaus, and thus don't justify the purchase of expensive digital tools.

3.2 University Location B - Technische Universität Wien (TUW)

The main theme of the study cases is related to the structural vacancy of abandoned buildings. The local community is not necessarily the owner of these buildings, but has a dedicated interest to shift the potential decay. Within the setting of a design studio, approx. 20-25 students are working on a project theme and this delivers an adequate band with regarding the solution space (pool of ideas). The focus is laid on building program development on one side and to support decision-making processes regarding future use on the other side. Besides at least one local visit an exchange with on-site potential demands can be identified and translated into a design concept. In addition the communication with local representatives culminates on the occasion of the midterm and the final critique. After the termination of studio work once again an on-site presentation of a subset of the created designs takes place and intends to keep the discussion in the local community alive. Eventually realization as an option may occur.

Risk has another dimension in this regard. For the participating students there exists a risk not to complete their studio work with a sufficient grade. However, this type of risk is in other studio settings existing as well. On the other hand, the local community may consider risk in the sense of unsatisfied expectations, uncontrollable reactions from the part of the local residents, or simply waste of time of decision-makers. This type of studio work has been executed for a number of years and the work with 20+ students (level: master studies) did not lead so far to bitter disappointments at all. The aim is not to bypass professional architects, but to take up design tasks, which are otherwise neglected (too small; not paying off etc. in a professional office environment). However, when it comes to realization several options exist to link up participation students with professional architects.

3.3 Digital Necessities as Part of the Design Process

In regards to teaching digital strategies and workflows in architectural planning, the strength of the didactic format of the "Experimental Bureau" lies first and foremost in being a catalyst for intrinsic prioritization and choice of the digital tools deemed necessary by the students (fig. 4 shows a workflow generated within case study example III). This process can be moderated and supervised by academic staff but it is primarily fueled by the reference to the necessities that are inherent in the real-life project and the needs of the external partners. Thus the pressure to decide what software and hardware is put to use is based on real needs, thus adding motivation on part of the students in getting to know and implementing them, and not a curriculum that may be looked upon by them as artificially imposed.

As an element of meta learning, or as Bateson called it deutero learning (Bateson 1978) students re-

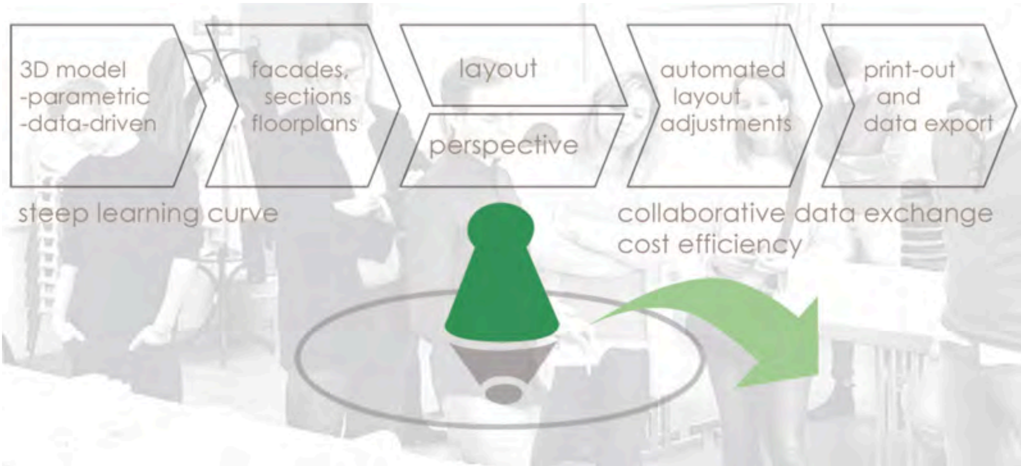

Figure 4
Digital workflow necessities in the Experimental Bureau

alize (if guided accordingly) that a choice of digital tools may be sensible in regards to one project and futile in regards to another. In the following examples this variety of prioritization of digital necessities per project becomes obvious.

Example I: CAD / CAM Strategies - "IBA Musterwohnung" (HCU / TUHH). The process of realization of the interior design of the "IBA Musterwohnung" called for digital strategies involving among others computer-aided manufacturing by CNC-milling machines. The authors of the winning concept in the student competition had to deepen their knowledge about CAD/CAM APIs to see their design ideas materialize.

Example II: Public relations by digital imagery - "Rathauspassage" (HCU). Setting out to design the interior of the "Rathauspassage", a social workplace right next to the Hamburg's city-hall, but underground with no immediate contact to public space on the surface, it soon became clear, that the customer not only wanted a design solution addressing this problem, but also imagery to use in a public relation strategy. This was communicated to the students by the customers themselves and further discussed within the group that wanted to take part in the preliminary student competition. As expected, the group with the best pictorial communication, as well as a high quality design, succeeded with the jury. Finally their image, as a result of 3D modeling, rendering and collage technique in image refinement software, was used as intended by its creators to communicate the customers intentions.

Example III: Digital workflow / parametric design - "BHH Sozialkontor" (HCU). Digital strategies, which were agreed upon by the group and put to use in the course of the design-development were e.g. digital enhancement of sketches and 3D models (fig. 5) with image refinement software and 3D modeling and rendering (fig. 6). These techniques were used in different stages of design development and customer communication.

Figure 5
Coloring of a 3D model with image refinement software (digital sketch)

Figure 6
Rendering of the situation presented in fig. 5 by Tom Ehlers

The curvature of the facade of the entrance area justified the application of parametric modelling in Rhino and Grasshopper (fig. 7).

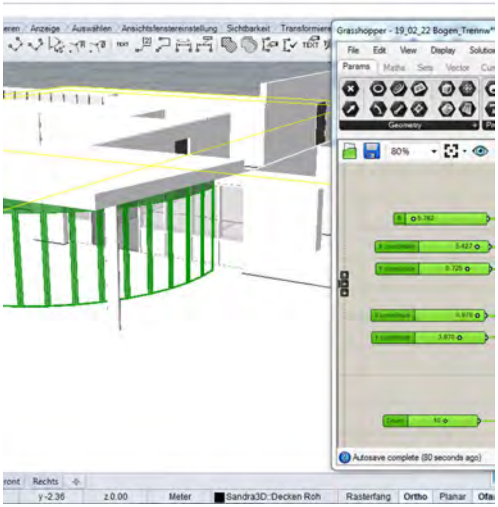

Figure 7
Parametric design for curvature and grid of the new entrance facade

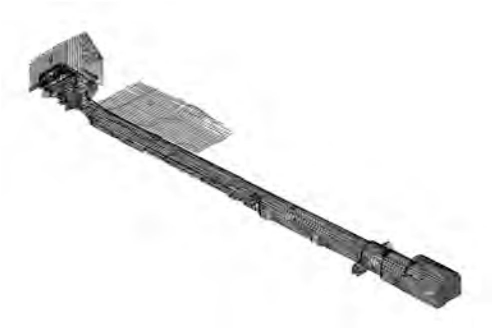

Figure 8
Raw data of the laserscan

Example IV: Use of laserscan data - Design Studio "Wine & Space" (TUW). In many places, wine cellars have lost their original function. Many a "Kellergasse" (Austrian expression for a lane or hollow way lined by wine cellars on one or either side) is on its way to dereliction, as most of the cellars are no longer in use. How can the abandoned premises be put to best use? How can they be filled with more daylight, which might be needed for new functions? Looking at the site from a design perspective also had to include issues of zoning and developing economically viable concepts of use.

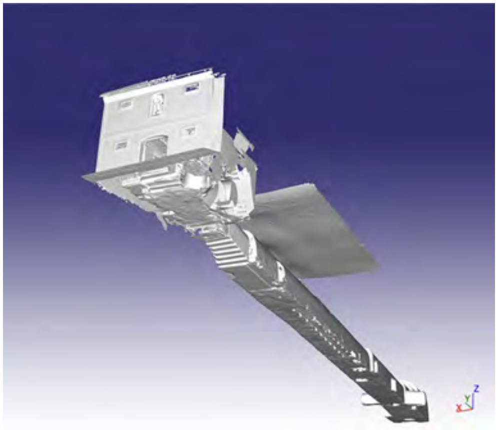

Figure 9
Result of the laserscan - digital representation of a cellar corridor

A building survey comprising of plans etc. did not exist and it would have been rather cumbersome for an individual student to work this out.

However, surveying data is rather meaningful to support the design process of the relatively complex geometry and allows to explore a common ground when working out design alternatives and solutions. For this reason a laserscan (fig. 8-9) was carried out in the beginning of the term and made available to the participating students.

Example V: Walkthrough representation of a final design (TUW). This design program focused on the old smithy at the centre of Mühlbach am Manhartsberg in the Weinviertel region. While the location is certainly attractive, the building has long ceased to fulfill its original function and has been vacant for quite some time. The first task was to devise a meaningful use for the building, but also think about how to animate the entire centre of Mühlbach in the vicinity of the local castle. The design concept is not to end at the outer walls of the smithy but should make an impact on the village fabric including the impressive castle grounds.

Figure 10
Exploration of the design by way of a walkthrough-representation on a tablet (TUW - Alexander Schaukowitsch)

One of the participating students developed a presentation of his concept in a walk-through environment (fig. 10), in order to facilitate the understanding of the design by laymen.

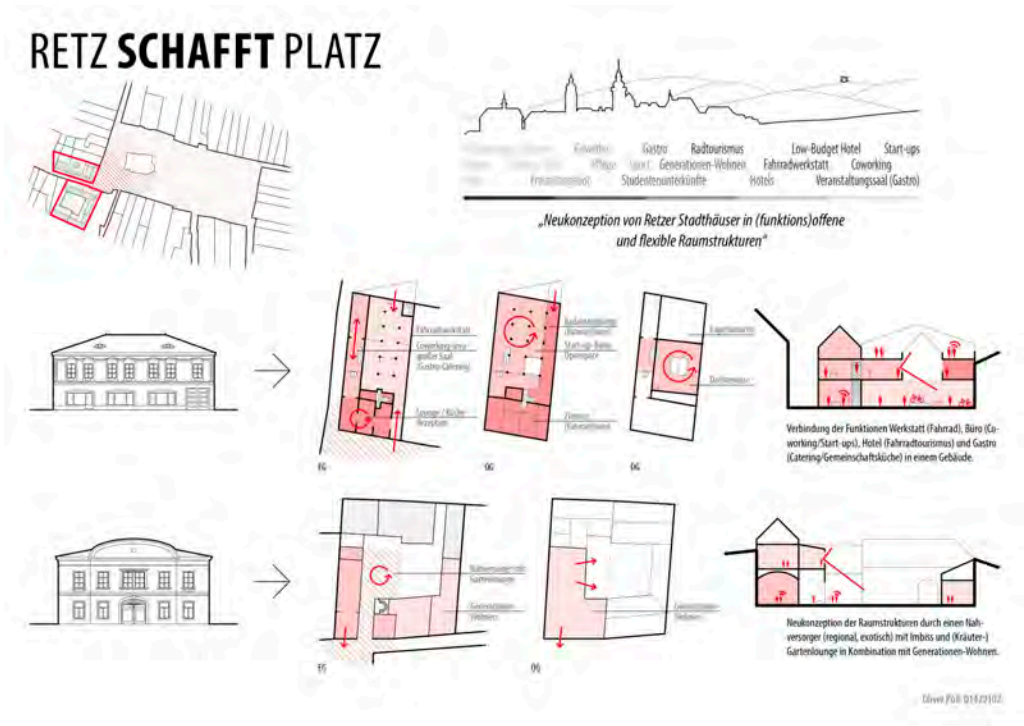

Figure 11
Example of an A3-sheet used in a plenary presentation (TUW - Oliver Pöll)

Example VI: Visual communication of early design stage concepts (TUW). At the very beginning of design studio a typical issue is to engage all students. It does not surprise that watching and observing what others are doing is more than tempting instead of a pro-active attitude to develop design concepts. For this reason a novel start of the design studio was developed by way of a mandatory assignment. Preceding to the first supervision meeting students have to work out an A3-sheet with a comprehensible concept idea (fig. 11). This document has to be submitted to the e-learning environment before the meeting and will be projected on a large screen. Although the procedure sounds too easy it has proven to be beneficial as anybody has to participate and cannot "hide" with for example a small sketch. Overall it leads to engagement and common discussion. This step may be - depending of the overall design assignment - repeated once again, if needed. From here on individual supervision takes place in the setting of the whole group of participants, i.e. presentation and review one by one.

4 CONCLUSION AND OUTLOOK

In this paper the laboratory environment of the "Experimental Bureau" aiming to explore and steer real-life design tasks has been elaborated by way of accumulated experiences at two different institutions. Several different types of assignments in the context of architectural design have been presented in order to show the meaningful implementation within the context of a design studio. The overall aim is not to completely replace previous "abstract" assignments, but to achieve a balanced mixture between fictitious and real-life exercises. Particularly issues of scale and dimension require sincere guidance as the accompanying framework conditions are predeter-mined and adaptation is restricted.

The process of self-organization - with a certain degree guidance - serves the teambuilding within the group students and does not ignore the requirement of delivering individual contributions. Sharing data, but also common model building (typically: urban fabric model) play a central role. On top of this, the settings do reinforce the intrinsic choices of digital tools as well. The issue of software usage is sensitive especially when a commercial context comes into place.

Within the group discussion an exchange on the effect of imagery ("idiosyncratic impact") and the communication with stakeholders delivers invaluable insights regarding perceptional phenomena.

The inquiry into the characteristics of each example from the viewpoint of digital necessities required to solve real-life design tasks, mainly identified by the students confronted with these projects, may be regarded as a qualitative study on digital strategies in architecture and design. It reveals first and foremost that the digital necessities are diverse and their diversity is the result of the individual framework, demands and needs related to the project as well as the digital strategies to tackle the task are chosen according to individual characteristics of the team determined to meet it.

Within the format of the Experimental Bureau supervisors can positively confine themselves to the role of coaches and moderators - as questions arise on how to proceed they can reference the real-life problems and settings of the projects as well as the stakeholder statements during critiques and discussions.

The motivation to work on the real-life design task is more directly devoted to its problems that need solving - it is less attached to grades, titles and the desire to meet the teachers' expectations. If an actual customer is convinced of the helpfulness of a design concept, among others through the choice of the right digital strategy, a different kind of professional confidence can be learned by students. Digital empowerment in this context means also that, according to Bateson reflections on deutero learning, students not only learn to work with digital tools but to chose what they need to learn at the time they need to learn it.

To trigger this kind of learning the Experimental Bureau resorts to real-life, even adventurous experience (see on the didactic potential of experience and adventure e.g. Boeger et al. 2005 and Miles et al. 1990). As contracts with customers are involved, so is an individualized learning which has been described as characteristic for contract learning (Gilbert 1976, p. 25). Although Gilbert refers to an individual agreement between teacher and student, contract learning may serve as a base for reflection on customer contracts within the format of the Experimental Bureau. Digital empowerment in this context is also a reference to empowerment education (Shor 1992) and its underlying concept of a democratized pedagogy as teacher and student mutually investigate and solve problems at hand.

All in all it is hoped that the readers of this paper might be encouraged to explore similar educational experience at their institutions.

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A Computational Design Workshop Experience for 21st Century Architecture Education

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With the rapid increase in the accessible data, available information surpasses one's ability to extract knowledge from, which puts a great emphasis on the skills of the individual to reach and use relevant information, adapt to changing conditions and sustain respective skills. ICT skills, critical thinking skills, and communication/collaboration skills emerge as the survival skills and key factors for individuals to cope with the demands of the 21st-century. It is known that educational institutions have struggles in changing the curricula/teaching system in coping with the requirements of the rapidly evolving industry. Thus, workshops gained more importance in different levels which are a part of curricular or extracurricular activities to re-furnish existing skills or gain new skills. In the scope of this study, the learning and teaching approaches based on STEAM approach are assessed through a three-day workshop aiming to illustrate how these survival skills can be conveyed and embedded into the architecture education. The workshop is designed to be inclusive for all architecture students regardless of their level of education or background knowledge/skills. Within the scope of this paper, the conduction strategies of the workshop are covered in detail to highlight the importance of these survival skills along with the modes of teaching and share the best practices and gained knowledge for future works.

Keywords: *Computational Design Workshop, Architectural Education Strategies, Survival Skills*

1. INTRODUCTION

Today, the prevalence of interactive technologies has yielded to the emergence of new learning environments in which learners expected to take responsibility and control of constructing a new medium through their own experience. With the rapid increase in the accessible data, available information surpasses one's ability to extract knowledge from, which puts a great emphasis on the skills of the individual to reach and use relevant information, adapt to changing conditions and sustain respective skills. ICT skills, critical thinking skills, and communication/collaboration skills emerge as the survival skills and key factors for individuals to cope with the demands of the 21st-century.

This dramatic change not only forces learners to adapt themselves but also puts great pressure on all educational institutions and teaching-learning environments to raise individuals to meet these demands, and architecture schools are not exceptions. In this respect, an Erasmus+ project named "ArchiSTEAM: Greening the Skills of Architecture Students via STEAM Education" is conducted with researchers from Middle East Technical University (METU), University of Bologna (UNIBO), and Aalborg University (AAU). The project addresses the current demands, and the 21st-century survival skills are scrutinized. STEAM (Science, Technology, Engineering, Arts and Maths) approach is chosen to prepare architecture students by furnishing them with skills required to endure continuously changing technologies, accumulating knowledge and dynamism of 21st-century. The STEAM approach, which does not aim to deliver the components in an isolated manner but aims to provide any content by achieving the harmony between these components. ArchiSTEAM Project also delivers STEAM-based teaching modules to foster these skills regardless of the course or subject to be delivered; but considering the instructional objectives, type of content, teaching/learning activities, and the role of evaluation. As an attempt on the conduction of the proposed teaching and learning practice, a series of workshops are organized in Ankara, Bologna, and Aalborg aiming to evaluate the proposed modules in different contexts and in a short period of time. Both the project and the workshops aim to deliver and validate STEAM modules which can be conceptualized as self-contained "units" of content that with other such segments constitutes an educational course or training program [1]. In this paper, the workshop conducted in METU (Ankara) is presented with respect to the targeted outcomes of the project.

It is known that educational institutions have struggles in changing the curricula/teaching system in coping with the requirements of the rapidly evolving industry. Thus, workshops gained more importance in different levels which are a part of curricular or extracurricular activities to re-furnish existing skills or gain new skills. Although, upskilling survival skills are beyond the objective of any workshop, limited and relatively short duration of the experience not only provides an adequate medium for experimentation of novel teaching/learning strategies and to support curricular activities but also leads the future adaptations of the curricula.

The presented three-day workshop aims to illustrate how these survival skills can be conveyed and embedded into the architecture education. The workshop is designed to be inclusive for all architecture students regardless of their level of education or background knowledge/skills. For this purpose, the workshop is conducted with students from 16 different universities at different levels of education (2nd, 3rd and 4th year). Within the scope of this paper, the conduction strategies of the workshop are covered in detail to highlight the importance of these survival skills and share best practices for future works.

2. DESIGN OF THE WORKSHOP AND THE EXPERIENTIAL LEARNING ENVIRONMENT

The skills targeted for the workshop are designed to include a number of STEAM Skills (33 skills from three skill-sets: Information and Communications Technology, Ground Skills,and Problem-Based Learning Skills) that are defined in the project [1] to epitomize the STEAM modules in a short duration implementation. The workshop is constructed to reflect the phases of design, from the reformulation of the problem to design and fabrication. Hence, it is aimed to inspect the feasibility of the experiential learning scenario to form a basis for future implementations in longer durations, e.g. training, courses or complete curricula. Therefore, the objectives of each working and presentation session selected accordingly. The aimed skills and the related sessions are shown in Table 1. The session names are as follows: (1) What is Cocoon, (2) What is cocoon in architecture?, (3) Ready-Set-Go, (4) Showtime, (5) Design your own digital ecosystem, (6) Pack Yourself, (7) Hibernation Time, (8) Weave your cocoon, (9) Wrap up, and (10) Final Presentation and Exhibition. It is seen that the covered skills are adequate to reveal the potential of the experiential learning scenario.

3. PROGRAM AND STRATEGIES

The workshop is designed based on strategies that are defined to provoke the creativity by liberating the students from the constructs of their own discipline in a collaborative environment while working in a limited time. Therefore, timing and objectives are controlled via a tight program prepared and distributed at the beginning of the workshop (Figure 1).

In this program, the balance between social

Table 1
The aimed skills and correspondent sessions for Cocoon Workshop

Skill Identifier	Skills	1	2	3	4	5	6	7	8	9	10
ICT-A1	Being able to conduct in depth research in relation with the problem	•	•	•				•			
ICT-A2	Being able to collect relevant information	•	•	•				•			
ICT-A3	Being able to use different search tools and medium	•	•	•				•			
ICT-A4	Being able to conduct smart search by using a number of combination of keywords	•	•	•				•			
ICT-B1	Being able to acknowledge the limitations and potentials of software and choose appropriate tools for given task			•	•			•	•	•	•
ICT-B2	Being able to produce data in different media			•	•			•	•	•	•
ICT-B3	Being able to transfer data to different media			•	•			•	•	•	•
ICT-C1	Being able to cope with digital collaboration tools	•	•	•				•		•	
ICT-C2	Being able to utilize cloud based technologies	•	•	•				•		•	
ICT-E1	Being able to troubleshoot software and hardware problems									•	
G-C1	understand the application of the mathematical and physical principles underlying the architecture and engineering sector							•	•	•	
G-C2	Being able to utilize tools for the management of technical information									•	
G-C3	Being able to work independently and in a team	•	•	•				•		•	
G-C5	Being able to identify, formulate and solve complex problems that require an interdisciplinary approach			•		•	•	•			
G-C6	Being able to communicate the results of your work graphically, through presentations and technical reports				•		•		•		•
PBL-A1	Being able to identify and define search terms	•	•	•				•		•	
PBL-A2	Being able to select the proper sources for the search	•	•	•				•		•	
PBL-A3	Being able to summarize and conclude the search	•	•	•				•		•	
PBL-A4	Being able to understand the purpose of taking notes	•	•	•				•		•	
PBL-A5	Being able to use note-taking techniques	•	•	•				•		•	

Skill Identifier	Skills	1	2	3	4	5	6	7	8	9	10
PBL-A6	Being able to sort and use notes for writing	•	•	•				•		•	
PBL-B1	Being able to establish a common understanding of a certain task	•	•	•		•	•	•		•	
PBL-B2	Being able to organise work between multiple individuals in order to solve a certain task	•	•	•			•	•			
PBL-B3	Being able to optimise own and others work by sharing individual work to a common result	•	•	•			•	•			
PBL-B4	Being able to understand the dualism between a problem and solution space			•				•		•	
PBL-B5	Being able to identify a problem					•	•			•	
PBL-B6	Being able to clearly formulate the problem					•	•				
PBL-B8	Being able to define criteria for a viable solution			•				•			
PBL-B10	Be able to evaluate concepts and solutions that solves specific problems							•			
PBL-B11	Be able to decide upon what solution to choose based on systematic evaluation							•			
PBL-B13	Being able to identify project goals and project limitations					•	•				
PBL-B14	Being able to manage the scope, timing and quality of a project					•	•				
PBL-B16	Being able to understand the open-ended and iterative nature of a problem-based project					•	•				
PBL-C1	Being able to use basic drawing tools							•	•		
PBL-C2	Being able to use basic drawing techniques							•	•		
PBL-C5	Being able to apply drawing/modeling skills in the process of sketching							•	•		
PBL-C6	Being able to evaluate sketches as a basis for new sketches						•				•
PBL-C7	Being able to iterate the problem formulation in order to narrow the solution space			•				•			
PBL-C8	Being able to define criteria for a viable solution			•				•			
PBL-C9	Being able to develop proposals that corresponds with the criteria for solving the problem			•				•			

Table 2
The aimed skills and correspondent sessions for Cocoon Workshop (cont'd)

activities, lectures, and hands-on working periods and presentations is determined carefully. And the schema showing the notation of the program (Figure2) is shared with the students at the beginning of the workshop.

The program is followed strictly to ensure the objectives to be met. Also, as it can be seen in the program, the workshop is organized to be taken place in many spaces in the Campus such as Digital Design Studio (DDS) and Computer Laboratory (CL) in Fac-

Figure 1
Program of the
Cocoon Workshop

ulty of Architecture and Design Factory (DF). While DDS and CL provide a suitable environment for research and design, DF provides an environment eligible for hands-on learning and fabrication giving the possibility to learning while doing.

Figure 2
Event types executed throughout the workshops

In this workshop, the students are expected to work in groups to foster a collaborative working environment which can also be described as a survival skill. The learning/teaching strategies adopted while designing the workshop are (1) pushing students out of their comfort zone by providing an ill-defined problem and directing participants to conduct an multi-disciplinary research, (2) scheduling by giving well defined tasks in a limited time and promoting punctuality, (3) scaffolding as an teaching activity, and (4) use of computational design as an enabler of survival skills.

3.1 Leaving the Comfort Zone

In order to promote creativity and enable students to gain new skills, pushing students out of their comfort zones plays a crucial role. For this purpose, three approaches are followed namely; i) providing an ill-defined problem, ii) forcing students to conduct research in multiple disciplines and iii) expecting students to merge and relate their findings in a meaningful whole serving the design objective.

Initially, the theme of the workshop needed to be an ill-defined problem forcing students to make research in different disciplines from various sources; hence, letting students open their minds to new perspectives in order to enhance imagination and creativity. Thus, "Cocoon" is given as the theme with brief information as "A cocoon is not only a protective shell but also is a morphogenesis space helping you to move from one state to another." Students are asked to design their own cocoon for their next state of themselves. A great concern is dedicated to the choice of the subject and to encourage students to leave their comfort zone. With a challenging topic as cocoon, it is aimed to stimulate designer's curiosity and creativity at one side and by forcing them to leave their comfort zone, it become possible to create a motivation to explore the subject in different fields.

Adapting principles from a biological phenomenon to architecture is proposed as an exercise to bring information from different disciplines together enabling students to experience information from other fields than architecture. The students are also encouraged not to limit themselves with Biology and Architecture and explore how other disciplines/fields use the Cocoon concept. By suggesting an exploration on the perspectives of other disciplines, this exercise has great potential for students to think out-of-box and broaden their understanding of space. In that sense, it is aimed to show students that the information retrieved from different disciplines are related with each other consisting the parts of a whole by showing the role of the architecture in this context.

3.2 Scheduling

Scheduling plays an important role in the design of the workshop as the duration of the event is limited and compressing the design and fabrication process in a three-day workshop is a challenging task. In contrast to "breaking the comfort zone" strategy, a set of very well defined tasks is provided to the students with respective expected outcomes of each task. The punctuality is persisted throughout the workshop.

It is aimed to conserve the iterative nature of design while supporting students with short lectures. The phases of the workshop can be summarized as research, reformulation of the problem, design, and fabrication. At each phase, the constraints of the problem are refined and changed with respect to the expected outcome forcing students to adapt themselves and their design proposals to the new situation.

3.3 Scaffolding

Scaffolding is a type of teaching activity in which coaches/mentors provide support to students needs. Scaffolding breaks the one size fits all understanding and enables the promotion of diversity in terms of knowledge/skills and levels of students. As the workshop is not limited with respect to the educational background or level of education, scaffolding is used as the primary teaching activity to enable students to gain expected skills and foster their knowledge with respect to their level. Each group is assigned a mentor which monitors and assures the progress of both the group and the individuals.

3.4 Computational Design

"Cocoon Workshop" is constructed as a computational design workshop. The computational design is embraced in design education for a while (Çolakoğlu, Yazar, 2007) (Oxman, 2008) however, with the rapid technological development, not only teaching the tools but also creating awareness on new technologies and enabling students to understand the logic behind these tools becomes essential. This idea brings us the concept of computational design which can be understood with modeling and production as an enabling medium to realize the strategies mentioned above.

Computational design by its nature is open to inclusion of different approaches which are mostly defined by the problem assigned or concerned by the participants. In this regard, it can be considered as a powerful mean to foster multidisciplinary studies and related skills expected in the course of time. It is possible to claim that computational design problems are not only ill-defined problems like other design problems but also, they are problems forcing designers more to create their own design ecosystems including appropriate soft and hard technologies. Thus an experience-based environment offers great potentials to substantiate the role of interdisciplinarity and lifelong learning in design education and to further develop new pedagogic approaches to reinforce the related design skills.

4. IMPLEMENTATIONS: PROJECTS AND RESULTS

The workshop is documented with many photos, time-lapse footage and outcomes of the projects by means of posters and physical models. In addition to this report, the images and an informative video are shared via the project website [2] and announced to the public via social media pages of the project and the official web page of the department of architecture.

4.1. Daily Tasks and Final Outcomes

As shown in the previous section, the workshop is designed to include various types of activities i.e. lectures, hands-on working periods, presentation and social activities. As a result of these activities, students are expected to achieve 3 Milestones and present them to the tutors and other students. Initially, the groups are asked to make a quick presentation which is limited with 5 minutes on the gathered research findings of what cocoon is from various fields on a single slide. This session is not only designed to achieve a milestone but also aiming to help students to gather and document the findings in a coherent way to proceed with information transfer into the architectural domain which is the second milestone of the workshop. At this phase, students are asked to relate and map the information that they obtained from different disciplines into the architectural domain. Findings and initial ideas of the groups are presented in 4-5 slides in 5 minutes by the students at the end of the first day (Figure 3). After the second presentation session, the groups started to work on their design solutions to achieve the final outcome of the workshop which is presented with a physical model and two posters representing the scenario, design process, fabrication, and the outcome. These processes are presented in the Figure 4.

5. DISCUSSIONS AND CONCLUSION

The workshop is evaluated by means of conducting pre-post surveys including multiple-choice and open-ended questions to measure participants' self-evaluation of survival skills and perception of STEAM and architecture relevance. In addition, the observations of mentors and reflections acquired in the colloquium held at the end of the workshop with the mentors, participants, and observers are used to analyze the success of the workshop and the STEAM approach in education.

The findings did not show any significant correlation between participants' performance, and age, gender, the institution or city of residency. In contrast, the level of education plays an important role in self-evaluation of the participants which can be explained with self-confidence. This confidence can be related with having more experience in similar projects and/or learning activities. On the other hand, pre and post-surveys revealed that, as the students approach the end of their undergraduate studies, this self-confidence blinds the self-evaluation. While second and third-year students reported low scores on their knowledge and abilities in regard to the STEAM skills, fourth-year students reported a

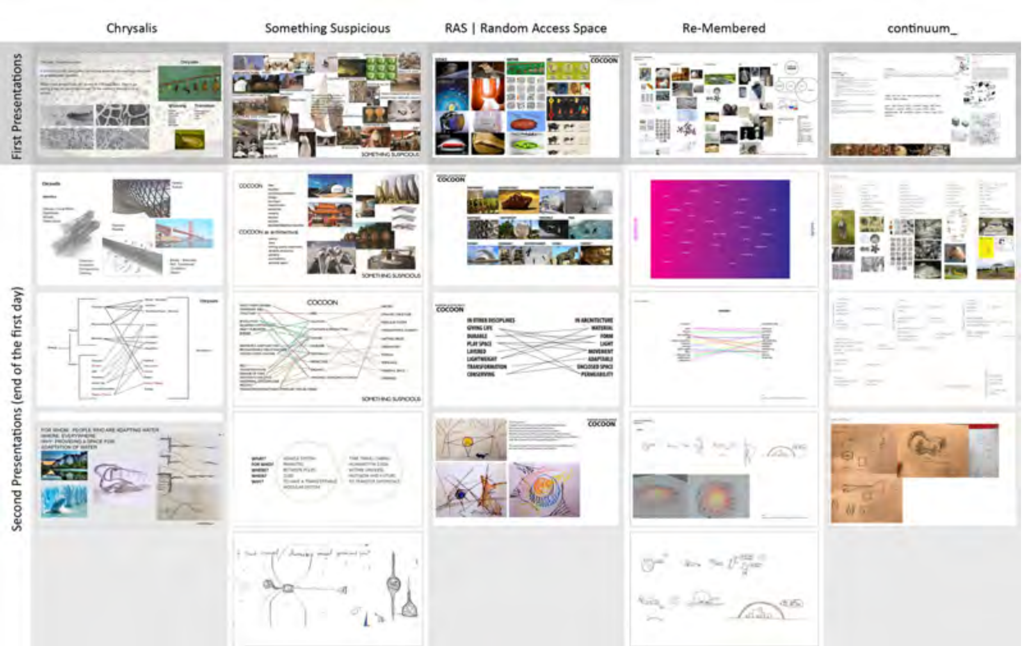
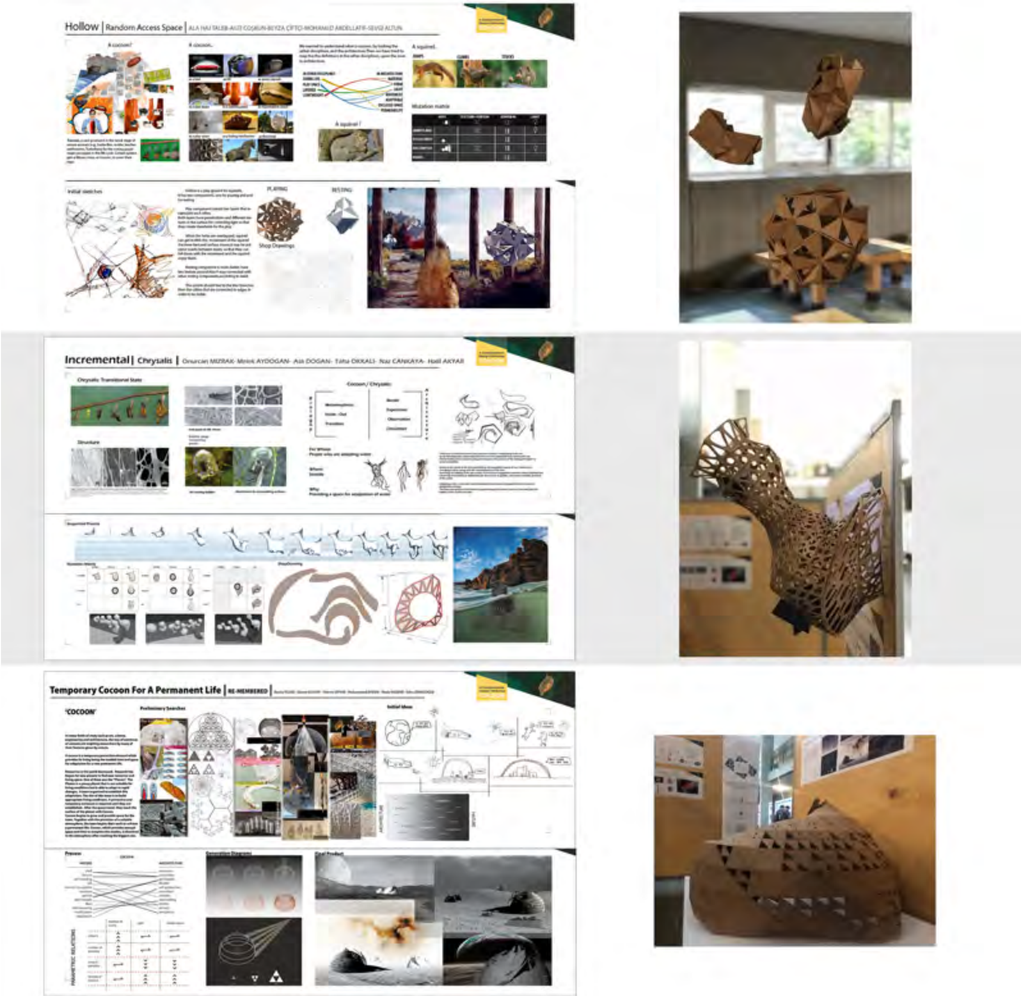


Figure 3
The outcomes of first and second presentation sessions

Figure 4
Some of the final outcomes of the workshop



high score in the pre-test. Correspondingly, a significant increase is observed second-year students whereas the fourth-year students reported slightly lower scores than pre-test responses. The results proclaim that pushing students out of their comfort zone also plays a crucial role in the self-evaluation and increase self-motivation to make up their lacking knowledge and skills. In this sense, the STEAM approach is generic and flexible and are able to reach to students regardless of the level of students. The responses to the open-ended questions regarding the reflection of the participants and the colloquium indicated that the workshop was a successful experience both for the participants and mentors in the realm of the project. The very first remark related to the workshop is the role of the subject or problem assigned. It is all accepted that curiosity and excitement motivate learning and thus, all the participants were so eager to explore what ″cocoon is″ and it was observed that subject matter was a key for triggering their creativity.

Secondly, it was observed that the role of the schedule was very crucial both for mentors and participants in fulfilling the required learning objectives and providing related outcomes. It was seen that students never lost their interest and their enthusiasm in these three days since each phase was new and challenging for them. The followed schedule and all the intermediate steps were means for them to have self-awareness of their progress. In every progressive step, it was observed that participants became more confident and more engaged in the learning process.

Finally, the role of mentors in the groups was very crucial and it was seen that they can effectively work in groups and be productive as long as mentors facilitate the design process by supporting them with proper assessments and coaching techniques with respect to the individual needs of the students and/or groups.

To sum up, the Cocoon Workshop is evaluated as a successful workshop not only in terms of the variety of the design results but also in terms of conveying the intended skills to the learners by means of the teaching/learning strategies forming the core of STEAM approach in architecture. In this respect, the workshop facilitated for the purpose of validating the outcomes of the ArchiSTEAM project along with other workshop organized by the University of Bologna and Aalborg University and course implementations in three universities.

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STEAM Approach for Architecture Education

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Starting with the first founded university, higher education has been evolving continuously, yet the pace of this evolution is not as fast as the changes that we observe in practice. Today, this discrepancy is not only limited to the content of the curricula but also the expected skills and competencies. It is evident that 21st-century skills and competencies should be much different than the ones delivered in the 20th-century due to rapidly developing and spreading new design and information technologies. Each and every discipline has been in continuous search of the ``right'' way of formalization of education both content and skill wise. This paper focuses on architectural design education incorporating discussions on the role of STEAM (Science Technology, Engineering, Art and Mathematics). The study presents the outcomes of the ArchiSTEAM project, which is funded by EU Erasmus+ Programme, with the aim of re-positioning STEAM in architectural design education by contemplating 21st-century skills (a.k.a. survival skills) of architects. Three educational modules together with the andragogic approaches, learning objectives, contents, learning/teaching activities and assessment methods determined with respect to the skill sets defined for 21st-century architects.

Keywords: *STEAM, Architectural Education, Survival Skills*

INTRODUCTION

In our day, requirements for the individuals are rapidly changing and evolving due to the liberation of information . Exponential increase of accessible data which triggers competences and knowledge to expire and become obsolete faster than ever before. In this sense, sustainable learning becomes a very crucial issue to cope with the demands of the 21st-century, Industry 4.0 and beyond. Today, one of the most important goals is to transform existing economies to green economies. One of the prominent features of green economy is high dependency on the level of education. Hence, how education should be re-structured and enable learners to have new mindsets and furnish them with green and digital skills is a crucial issue for individuals to be a part of sustainable economy. These skills differ from traditional schools' outcomes in terms of not only being content-based knowledge. Correspondingly, critical thinking, creativity, communication, and collaboration have been proposed as the "Four C's of 21st-century learning" by the United States Based Partnership for 21st-century skills which is a non-profit organization founded in 2002 [7].

Educational research studies are looking for ways to enhance students' learning and equip students with skills that are helpful to meet the 21st-century's demands (Retna, 2015). Easy access of information and high availability of technology makes our lives easier; yet, the definition of being a successful student and significant factors that are necessary for being successful both in academic and professional life has also changed. Architectural education is not an exception in this sense.

Architects of the past, or today or the ones in future should be able to incorporate and conduct a large amount of knowledge and data as well as to be able to cope with changes related with technology, culture, sociology, economy and more. They are expected to be creative and innovative in order to compete and to survive in the world of change. STEAM (Science, Technology, Engineering, liberal Arts and Mathematics) which is a holistic educational perspective of all these fields is a very promising structure in architectural education. The idea of STEAM actually exists almost in every curriculum of schools of architecture implicitly at varying levels of integrity. Yet, revisiting the contemporary curricula of architecture schools from the principles of STEAM approach provides an opportunity to revise the skill sets and learning outcomes of the education with respect to the everlasting demands of the time in a more flexible structure.

In this regard, ArchiSTEAM Project, which is an EU-funded Erasmus+ Project, is conducted with the collaboration of Middle East Technical University (METU), University of Bologna (UNIBO) and Aalborg University (AAU) to analyze the architectural education and the relevance of STEAM approach, and to develop teaching/learning modules to enable the integration of STEAM mindset to the existing curricula of architecture schools.

STEAM APPROACH IN ARCHITECTURE EDUCATION: ARCHISTEAM APPROACH

Education technologists and academics try to improve their students' 21st-century skills by using different learning approaches. Science, Technology, Engineering, Math, Art (STEAM) education is one praxis of efforts. STEAM education contains skills, knowledge, and beliefs that are collaboratively constructed at the intersection of more than one STEAM subject area (Corlu et al. 2014). The STEAM approach in teaching aims to prepare individuals with high creative and innovative skills and to improve learning outcomes and prepare students to the era that we live in. In this respect, the STEAM approach offers more than the sum of all parts (disciplines) and focuses on how to blend these disciplines in harmony for further understanding. Correspondingly, The STEAM approach fundamentally deals with the modes of conveying the skills and knowledge rather than combining the subjects in focus. Moreover, STEAM provides a teaching frame for instructors from different fields to create a progressive learning environment for students. It is a catalyst for students to combine their science and art skills to provide innovative solutions to challenging problems of the real world.

STEAM experiences involve two or more standards from Science, Technology, Engineering, Math and the Arts to be taught and evaluated through each other. On the other hand, students' understanding of how things work can be increased, and their use of technologies can be developed by a true STE(A)M education (Bybee, 2010). STEAM approach centralizes on inquiry, collaboration, and an emphasis on process-based learning aiming for exploring new and creative ways of problem-solving, displaying data, innovation, and linking multiple fields. STEAM provides more real-life connections to students and teachers, and through a powerful combination of topics and techniques for educating our society is aroused.

It is a long and controversial debate "how design education should be" and "what is designerly way of thinking". In all these discussions, what is consented is "design is one of the most advanced thinking skills" for which constructivist learning becomes the core. Constructivist learning is the way for the mind to transform data into knowledge based on experience. Dewey (as cited in Bhattacharjee, 2015) argued that human thought is practical problem solving, which proceeds by testing opposing hypotheses. These problem-solving experiences occur in a social context, such as a classroom, where students join together in manipulating materials and observing outcomes. (Dewey, as cited in Bhattacharjee, 2015) Since it is relying on a student-centered approach, students are encouraged to use active techniques (experiments, real-world problem solving) to construct knowledge. By designing and performing a number of teaching practices for a well-planned learning environment, the students learn how to acquire knowledge and learn.

It should be highlighted that constructivism is not a teaching model, but it is a frame of thought; an ideology based on three main learning strategies: experiential learning, problem-based learning and project-based learning for which learners are actively engaged, i.e. it is learner-centered. When design education in the focus of studios is considered, either project-based or problem based, experiences will serve in developing such a constructivist mindset. In this process, the role of the instructor/mentor is crucial.

Unlike traditional approaches, constructivism modifies the role of the teacher by changing from active to guiding role for helping the student to construct knowledge. Constructivism requires active participation of students in the learning process rather than being a passive recipient of information as well as the guidance of teachers to construct students' knowledge instead of causing mechanical ingestion of knowledge by them.

In this process, it is evident that each individual has a different learning style. Kolb and Fry (1974) say that "knowledge results from the combination of grasping experience and transforming it." Accordingly, in this learning process, four main phases namely; experience, reflection, conceptualization, and experimentation take place. Successful experiential learning requires that each stage being mutually supportive of and feeding into the next. Hence controlling the learning process, properly designing the "learning environment" by the instructor/mentor starting from the assignment of the problem to the assessment, objectives, and outcomes become the key issues as well as the skill sets to be conveyed during the education and thereafter. Hence, revisiting design education with this perspective will help to restructure design education regarding skill sets that are expected from the graduates of architecture schools. For this purpose, firstly the framework for developing modules are constructed which is then implemented to architecture education within the scope of the ArchiSTEAM project.

MODULE DEVELOPMENT

Teaching modules are usually conceptualized as self-contained "units" of content. Multiple modules constitute an instructional course or training program. A unit can cover just one class or more. Likewise, a course may contain a variety of modules whereas a module teaches a complete skill or a meaningful content. It usually covers just one subject and is assessed independently of other modules in order to enable flexible/adaptable course design. According to Yelon (1996), Teaching modules are composed of 4 main components. Those are (1) Instructional objectives/Objectives, (2) Content, (3) Teaching/Learning Activities, (4) Evaluation.

Instructional Objectives	Content	Teaching/Learning Activities	Assessment
State your instructional objectives in SMART format	List Facts, Concepts, Principles and Skills related to the instructional objectives	Define the teaching activities (presentation, group discussion, project based learning, demonstration)	Define on the measurement type in accordance with learning objectives (Rating Scales and/or Checklist)

Table 1
Components of a Teaching Module [3]

	Facts	Concepts	Principles	Skills
Ideas	Organized set of facts	Definition of the category	Definitions relating variables	Ordered simplified steps
Examples	Vividly illustrated substantiation	Typical example-non example pair	Evidence showing relationship between variables	Demonstration

Table 2
Sub-categories of Module Content [3]

Instructional Objectives

Instructional objectives can be viewed as outcomes of the instruction. In other words, instructional objectives are the description of the knowledge and skills that we want students to gain during the instruction. Although there are several approaches for writing effective instructional objectives, S.M.A.R.T. method (Doran, 1981) is chosen within the scope of ArchiSTEAM project. S.M.A.R.T. The acronym stands for:

1. Specific: Make sure that objectives make the same sense for all including students and instructors.
2. Measurable: Remember that unless you define observable outcomes, you cannot know whether learners gained the necessary knowledge and skill at the end of the instruction. Thus, the student's performance must be measurable by both quantitative and qualitative criteria.
3. Action-oriented: Make sure that you use action verbs in your objectives so that student's performance can be evaluated.
4. Realistic: Make sure that expectations from the students are realistic in terms of conditions and time given.
5. Time-Based: Make sure that students are given proper time to attain objectives.

Content

In his instructional design model, Yelon (1996) links content directly with the instructional objectives, methods, and assessment. It means instructors are required to teach students related content that will help them gain the necessary knowledge and skills to achieve learning outcomes and to perform successfully on the assessment. The content should be relevant, appropriate to the students' background and their learning styles and structured to provide a meaningful learning experience. Yelon (1996) refers to content as "essential content to teach" and claims that essential content has 4 sub-categories (or types of knowledge to be taught): (1) Facts (2) Concepts (3) Principles (4) Skills. The underlying assumption behind categorizing content under 4 themes is that each type of content requires different mental processes and efforts to be learned. These subcategories are defined and exemplified in Table 2.

Teaching / Learning Activities

Teaching/learning activities are related to the activities conducted to convey the desired instructional objectives to the learners. In their work, Joyce, Weil & Calhoun (2008) categorized teaching methods under 4 main themes as Social Interaction Family emphasizing the relationship of the individual to society or to other persons. Gives priority to the individual's ability to relate to others, Information Processing Family emphasizing the information processing capability of students, Personal Family emphasizing the development of individuals, their emotional life and selfhood, and Behavioral Modification Family emphasizing the development of efficient systems for sequencing learning tasks and shaping behavior.

Assessment

Assessment is the most crucial component of an instructional model due to its nature. Assessment requires collecting systematic data about the students' progress in the learning environment. This data serves for several instructional purposes such as providing evidence about how instructional objectives are realistic or attainable by students, indicating the effectiveness of the teaching method assessment and providing evidence to make a judgment about the students' performance. Rating scales and checklist are some of the most frequently used assessment tools.

ARCHISTEAM MODULES

With the continuous development of technologies and accumulation of data, the expected knowledge and competencies are expiring rapidly, affecting every profession including architecture. In this respect, the STEAM modules in architecture (ArchiSTEAM modules) are focused on the generic skills relevant to architecture which will provide learners necessary tools to cope with the changing demands of the field and professional life. Correspondingly, the modularity and flexibility of the modules became prominent features of the developed modules. The primary objectives of ArchiSTEAM modules can be expressed as follows:

- The modules should be skill based instead of knowledge based in order to be adaptable to changing requirements of the era
- The teaching/learning activities should foster creativity
- The modules should create self-awareness and self-motivation for life-long learning
- The modules should foster professional soft skills
- The skills of the modules should be relevant to architectural education yet be generic to enable implementation in any course within the curricula
- The modules should be flexible in terms of conduction time and serve for varying durations of teaching activities such as workshops, courses or entire curricula
- The modules should be consistent in themselves to enable standalone implementation

After conducting several surveys with instructors, students and professionals, and in-depth analysis of the curricula of three partnering universities representing different ecoles, the relevant and missing skills are determined. The detailed information of these surveys is present in 1st and 2nd project reports [1,2]. Correspondingly, the determined skills are grouped under three categories in order to develop coherent and consistent modules. These three skill sets are namely Ground (Baseline) Skills, Problem Based Learning Skills (PBL) and Information and Communication Technologies (ICT) Skills. Ground (baseline) skills are to facilitate adaptation/survival of individuals independent of their discipline, age or background. In general, these skills address challenges in professional life in terms of communication and collaboration with close connection with skills required to architecture profession. PBL Skills, on the other hand, enhance problem-solving abilities through experiential learning. It promotes solution oriented analytical thinking and decision making. Finally, another complementary skill set addressing ICT is proposed to enrich the capability of students not only to use rapidly developing information technologies but also to prompt to develop and challenge the technological development. These skill sets are actualized in three education modules together with the instructional objectives/objectives, module content, teaching/learning activities, and assessment methods. Each skill sets are also subdivided into several groups with respect to the shared content and teach-

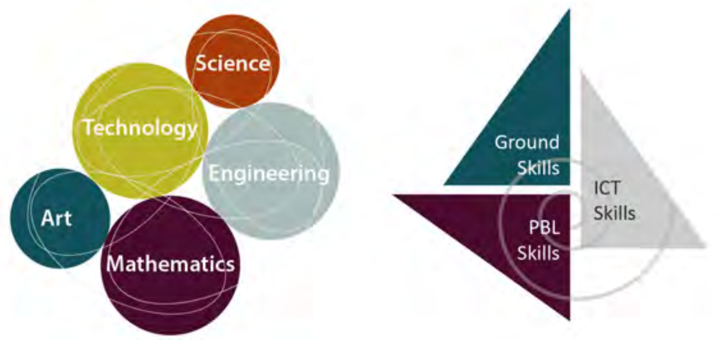


Figure 1
Intertwined nature of the STEAM approach and the ArchiSTEAM modules

Table 3
The ArchiSTEAM modules and the corresponding number of Learning Outcomes/Skills

ArchiSTEAM Modules	The number of Learning Outcomes/Skills determined
G-Ground Skills	**20**
G-A Design Process	6
G-B technical skills related to the control of structural and technological components	9
G-C Ground Skills	5
PBL- Problem Based Learning Skills	**64**
PBL-A General University Skills	18
PBL-B PBL-related skills	22
PBL-C Architecture and design-related skills	24
Information Communication Technologies Related Skills	**13**
ICT-A Information Retrieval	4
ICT-B Data Usage	3
ICT-C Collaboration	2
ICT-D Self Sustainability	3
ICT-E Troubleshoot	1

ing/learning activities.

It should also be noted that the skills and corresponding learning objectives were determined and formulized in such a way that they form a meaningful whole as well as being adaptable to any course. In this respect, these learning objectives do not aim to deliver a particular course content or knowledge but aim to foster the understanding of the learner for any course in architectural education. Yet, as the module definition brings the necessity of being self-contained units, the three ArchiSTEAM modules constitute overlapping learning objectives, e.g. "as being able to conduct in-depth research" with nuances in how they are put into words in PCL and ICT modules. The intertwined nature of ArchiSTEAM modules and the STEAM approach are illustrated in Figure 1. As a result, a total of 97 skills are determined, and the number of kills per module is shown in Table 3.

ArchiSTEAM modules are developed to be adaptable to any teaching practice, regardless of its duration and subject matter. Hence, they are usable in a variety of cases from a short workshop to the whole curriculum. In addition, these modules are constructed to form a basis for further development. Undoubtedly, the requirements of the next 20 years will be different from today's, and these modules should be renewed continuously in coherence with the objectives of education and in pace with current technologies. Education technologies and methodologies are also subjected to be revised/modified/altered in time. In this regard, any skill set such as provided here should be revised whenever necessary. The framework presented herein should be perceived as a guide reflecting contemporary needs and approaches. Moreover, it exemplifies the general rules of thumbs and principles of content and module design from a broader perspective. Hence, the schema presented within the scope of this project acts as a guideline and typical application of how to develop a framework for the aforementioned goals.

CASE STUDIES AND REFLECTIONS

The three STEAM modules proposed within the scope of the project are tested in two ways as; implementation in three different courses (Digital Design Studio, METU; Lab-based Course on Building and Architecture, UNIBO; Urban Technologies Course, AAU) at each partnering institutions [4] and testing through workshops organized in three different countries [5]. For the course implementations, the existing course syllabi are modified with respect to the ArchiSTEAM modules, and the maximum number of ArchiSTEAM skills are aimed to be implemented in coherence with the content of the courses to be implemented. For testing purposes, pre and post surveys are conducted with the students in order to trace the effect of integrating STEAM skills to the existing courses. Similarly, in order to test the flexibility of the modules in the time domain, three short workshops (1 - 3 days) are conducted in three partnering institutions in order to avoid cultural bias. Similar pre and post surveys are conducted with the workshop participants. The adaptation of ArchiSTEAM modules into education are found to be beneficial in terms of enhancing the understanding of the learners and delivering survival skills regardless of the duration of the training, cultural background, gender, age or educational background of the learners. Following reflections are documented with respect to the feedback from the learners and instructors who experience the integration of ArchiSTEAM modules:

- Assigning an open and ill-defined problems force students out of their comfort zone and broaden the understanding of the students by requiring them to confront with multiple disciplines, which positively influences both the design process and the final product.
- Multidisciplinary and problem-oriented approach motivates the students. Students are inspired by the implementations in other disciplines. Students are encouraged to come up with innovative ideas pushing their own limits.

- Cross-disciplinarity among the teaching staff forces instructors to engage mutually with each other's professional fields. Potential inter-relatedness of the discipline reflects the students' collaboration habits and being able to approach problems on a broader perspective
- ArchiSTEAM approach is beneficial for establishing high student motivation. This approach also enables high learning outcome, self-motivation of students, and cross-disciplinary approach to problem-solving. This is beneficial for both students and teachers, and it likely represents a strong and powerful trajectory in course development in higher education.
- The assessment process and means of assessments are crucial in the learning process in regard to setting the proper PBL environment and supporting the learning process of students.
- The STEAM approach as a way of structured integration of various disciplines invokes learning experience and furnishes creativity.
- ArchiSTEAM modules foster self-awareness of the students in terms of skills they acquire which promotes motivation to determine, revisit and renew expiring skills.
- The role of instructors which is practiced as mentors in the groups was very crucial. It was seen that students could effectively work in groups and be productive as long as mentors facilitate the design process by supporting them with proper assessments and coaching techniques

The knowledge and experience acquired throughout the project lifetime are compiled with a user-friendly interface to provide a guideline for the instructors who aim to follow a similar route to utilize the STEAM approach in their courses and education programs. This guideline is shared through the project website and is visualized in Figure 2.

CONCLUSION

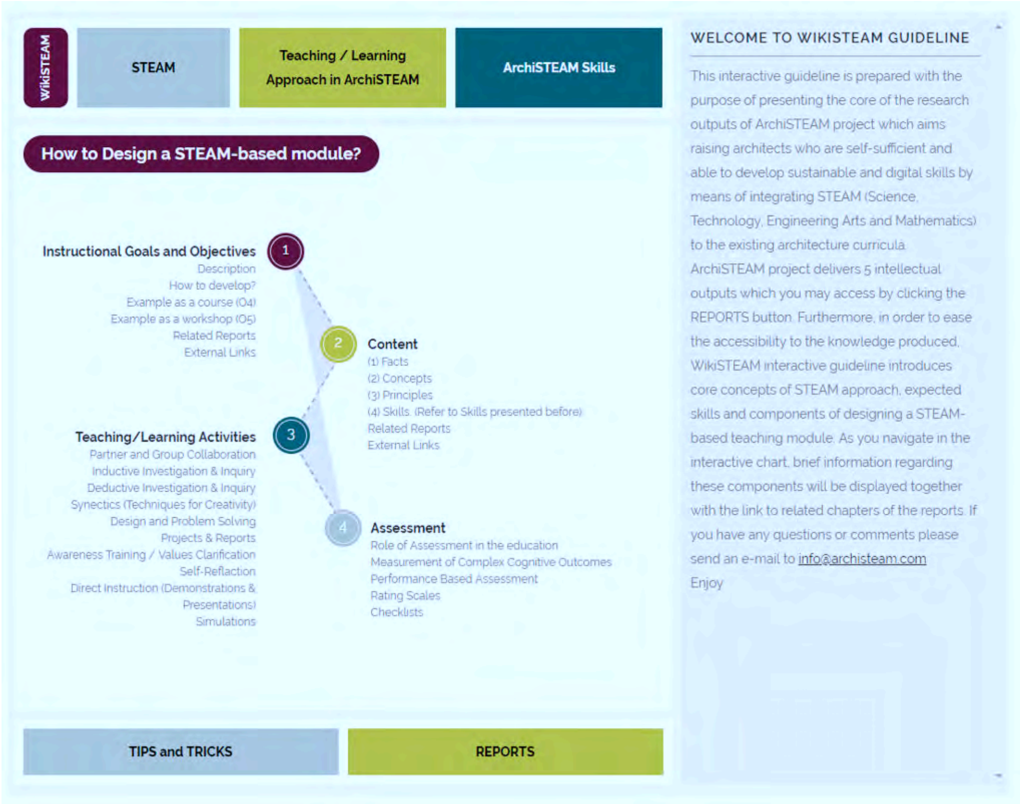
The ArchiSTEAM Project was a two-year project aiming to provide the ground to establish a STEAM approach in architectural design education. The STEAM approach is considered as an enabler for architecture students to work in an interdisciplinary way, and to approach design problems in a broadened perspective in their profession. It is also strongly advocated that the STEAM approach brings innovation and creativity into the design process.

It is evident that architectural education and especially design education has always been a controversial issue and each school has its own way of structuring their curriculum, and yet what is most common is the implicit implementation of STEAM. It is believed that the analysis of current curricula and revisiting the learning outcomes/objectives with respect to the STEAM approach and sustainability perspective will provide the opportunity to reshape architectural education to prepare students for the era which requires the ability to adapt to changing needs rapidly.

In the field of architecture, three skill sets - ground skills, PBL skills, and ICT skills - on top of the professional skills that are gained during education are essential for students, not only in their span of education but also in their professional life. These skills can be considered as green skills for the sustainability of their profession. In this sense, the STEAM approach is used as a guideline for determining the 21st-century skills and the modes of conveying those skills to the students together with the outcomes / possible content / teaching activities and assessment methods. The STEAM approach also serves as a way of structured integration of various disciplines to invoke learning experience and furnish creativity.

As a result of this study, three flexible and adaptable teaching modules are developed as an exemplary implementation of STEAM in architecture with respect to the determined STEAM skill sets. These modules are suitable for integration to any course or training as well as permitting to a stand-alone application. It should be noted that also the learning out-

Figure 2
WikiSTEAM
Guideline [6]



comes/objectives are not definite and should be revised with the changing technologies and modes of learning in time. In this respect, the project aims to deliver a guideline for the andragogy of architectural education for sustainable learning and green skills for the 21st century.

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Notes on Digital Architectural Design in the Undergraduate Teaching in Brazil

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This study focus in design process that uses the digital environment in context of undergraduate courses of Architecture and Urbanism, mainly the Digital Architectural Design (DAD). From author's previous studies that classified the teaching practice in Latin America, the Brazilian data were analyzed due to its expressive and heterogeneous features. Faced with a scenario that points to institutional characteristics reflect in the teaching approach, a horizontal mapping was performed. A data cross-referencing through correlation methodology was carried out. As result, there is a prevalence of public institutions that use teaching practice using DAD, most of them located at South and Southeast with a close link between teaching and research.

Keywords: *Digital Architectural Design, Levels of design computability, Mapping study, Teaching practices*

INTRODUCTION

This paper presents partial results of an ongoing PhD research, whose the main goal of this study is to map educational practices developed in undergraduate courses of Architecture and Urbanism in Brazil that explore the design process in the digital environment. In this way, this paper was planned to construct a layer of information that gives a base to discuss this subject.

Oxman (2008) refers to the acronym DAD - Digital Architectural Design - to describe the use of design methodologies fully supported by digital environment and exclude from this concept digital tools that only replicate analogical methods.

Faced the emergence of the DAD, it is understood that research on methods, tools and practices that have been developed in academic environment become extremely relevant. As Kalay says: *"Schools of architecture, therefore, have the responsibilities of understanding these changes, and guiding them, while educating new generations of architects who will use these methods, tools, and practices to change the environment in which we live."* (KALAY, 2009, pag. 6).

Researches about DAD concept are already established at least a decade ago. For at least a decade, tools that explore a language based on visual programming are being diffused in Latin America (HERRERA, 2011). On the other hand, Flório (2012) affirmed that Informatics have an operational and instrumental focus in Brazilian undergraduate courses. Following this trend, Celani et. al, (2017) evaluated the same context and observed that experiments using new technologies, including programming languages, are scare in the country and are still isolated experiences which focus in the software use. But studies with qualitative and quantitative information about the recent scenario are not yet available.

This study intends to fill this gap by mapping some topics of the current state of architecture teaching in Brazil, by means of crossing data about the use of new digital design technologies with qualitative and quantitative features of undergraduate courses.

In order to analyze recent developments in the region, the present study takes up previous studies conducted by systematic review (VASCONSELOS, SPERLING, 2016;2017). The aim of these studies was to mapping the state-of-art of DAD in undergraduate Architecture and Urbanism studies, from 2006 to 2015, in the Latin America context. This systematization was based on different modes of interaction between Designer and Representation in the design process in digital environment (OXMAN, 2006) and on the levels of computability: representational, parametric, and algorithmic (KOTNIK, 2010). Even if these topics had been focused in later works by these and other authors, the proposed framework by the combination of classifications proposed by Oxman (2006, 2008) and Kotnik (2007, 2010) is still valid.

The parametric and algorithmic levels are associated with an advanced level of computability and established as DAD. The levels of computability are presented in Figure 1.

In the process of *Interaction with digital constructs* (OXMAN,2016) or in the *Level of design computability representational* (KOTNIK, 2010), the designer interacts directly with representation. And, as previously presented in Figure 1, it is basically composed by the class of CAD models. This level of computability is divided in: CAD descriptive model, Generation-evaluation CAD model, CAD descriptive models and their evolution to dual-directional digital process. From these models, designer and computer have a logic interaction similarly to the process developed on paper. In order to describe the similarity, Kotnik applies the expression *"electronic drawing tool"* (2010, pag. 8)

The *Interaction with a digital representation generated by a mechanism* (OXMAN, 2006) or the *Level of design computability parametric* (KOTNIK, 2010), the designer does not interact directly with representation. He interacts by a variable control of parameters that conform a mechanism to generate the model.

The *Interaction with digital environment that generates a digital representation* (OXMAN, 2006) or *Level of design computability algorithmic* (KOTNIK, 2010), the design process is developed from the interaction between designer and computational mechanism. The user identifies and explicitly criteria to guide the generative process. The generative process starts from algebraic, analytical and geometric operations that emerge an architectural object.

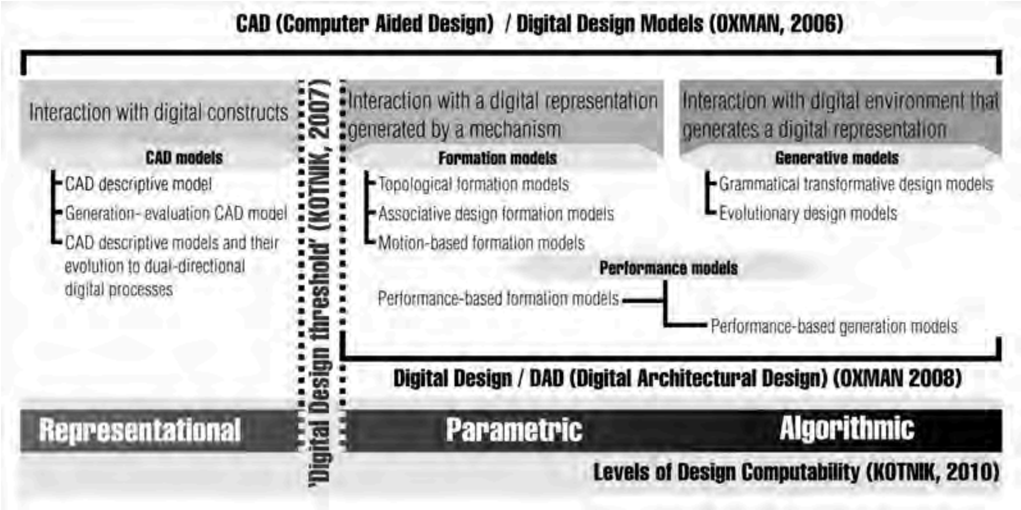
Therefore, from the previous systematic reviews and using data visualization (LIMA, 2011), it is proposed to analyze the specific scenario of the DAD in Brazil - the Latin American country with greater number and diversity of experience in the field (VASCONSELOS, SPERLING, 2016;2017).

METHODS

While the Brazilian system of universities is composed by public institutions, big private companies of education and small private institutions, the research system is almost all in public universities. Recent studies show that 90% of the Brazilian research is produced by the public sector (universities and research centers). Thus, our hypothesis is that mapping this scenario is relevant to understand what is going on in the specific context of DAD in architecture undergraduate courses in Brazil, drawing on some correlations. As Abrams and Hall says *"mapping has emerged in the information age as a means to make the complex accessible, the hidden visible, the unmappable mappable"* (ABRAMS, HALL, 2006: 12).

This research is based on a descriptive study (GIL, 2010) by means of a series of correlational analysis (GROAT & WANG, 2013). The correlational research is focused on patterns of relationships between two or more variables presented in the specific context. In our case, the data from the undergraduate courses were compared with the didactic practices according to the levels of computability mapped in previous studies (VASCONSELOS, SPERLING, 2016 ;2017).

Figure 1
Levels of Design Computability, categories and subcategories. Source: authors adapted from Oxman (2006,2008) and Kotnik (2007,2010).



The previous study was a systematic review that sought the CumInCAD database, until April 2017, and analyzes 13053 articles. The applied search strategy the following terms were used: educa (for education, educate...), teach (for teaching, teacher...), learn (for learning, leared...) e dida (for didatic). To be included in the review, the articles should obey the selection criteria: 1) studies performed between 2006 and 2015; 2) performed in Latin America; 3) carried out in Undergraduate level; 4) that explored the creative process in digital environment.

It is important to highlight that the accounting of the teaching practices was related to the year of publication and not to the year of its accomplishment, given the fact that not all the articles explain this data. However, even considering this bias, this systematic review contains the first mapping of DAD teaching practices in Latin America. It is also worth noting the importance of mapping and data collection that analyzes teaching practices carried out over a decade, using a research methodology based on a correlational study, which is validated by Groat and Wang (2013).

Our study focus on the Brazilian teaching practices, which correspond to 48% of the sample from the previous study. Figure 2 shows the methodological scheme of the study, the correlation between the systematic review with the mapping of institutions in Brazil.

Figure 2
Methodological scheme of the study.

DEVELOPMENT

Information mapping as a strategy for immersion on the context of Architecture and Urbanism teaching in Brazil

An information mapping of all the Architecture Schools in Brazil was performed The search was carried out from October 2017 to February 2018 on the database of the Brazilian Ministry of Education and Culture (MEC). Data were extracted manually and compiled in a specific table for the study (Microsoft Excel 2017, United States). The following variables were collected: Course score according to government agencies and national examinations; Number of authorized places; Modality and situation (classroom or distance learning; open, in process, closed); Course implementation (date); Administrative nature of the institution (private or public); City and state.

Initially, 690 undergraduate Architecture courses were identified, of which 18 distance-learning courses were removed. The final sample had 672 undergraduate courses, 591 are already implemented and working. This data was systematized and was presented in Figure 3, organized by important criteria related to the context, explained separately below.

From the data systematization, it is possible to observe the temporal period and location by regions about the implantation of Architecture and Urbanism In-Class courses in activity in Brazil (Figure 3, top part). Two periods of greater expressiveness related to the growth rate of courses are identified. The first occurred in the 1970s and the second in the present decade, with a growth rate of 192% and 174%, respectively. It is important to highlight that the last decade is not complete, since its analysis was performed in 2018.

In the bottom part of Figure 3, is observed the proportion between public and private institutions (left part), and the relation between institutions localized in Capitals and other cities (right part). This mapping was performed in three scales (national, regional, and states) to explain those differences.

The relation between public and private institutions demonstrate a higher number private institutions in most of states. However, this difference is not highlighted in the regional and national scales. There is a higher amount of private institutions in South and Southeast regions, and this relation also occurs in Midwest and Northeast regions. Only one state showed 100% of public institutions, whereas the number of private institutions ranged from 65% to 100% in the other states.

About the analysis of institutions located in Capitals or other cities, there is a significant difference between North and South regions. It is visualized a continuous, almost predominantly green spot in the South to Southeast regions. Also, the Midwest regions showed a heterogeneous relation between the states, the institutions localized in Capitals varied from 33% to 100%.

Teaching practices in terms of computability levels

During the classification process of experiments, it was verified that some of them could be classified between classes extracted from Oxman (2006) and Kotnik (2010) as it was observed the coexistence and transition between the levels of computability in a same didactic practice. Consequently, the initial classification was expanded and two intermediary classification were created (representational and parametric; parametric and algorithmic). Figure 4 shows the classification of the Brazilian didactic experiments between 2006 and 2015 according to levels of computability.

From the data of the analyzed period (2006-2015), the level of computability of 42.6% of teaching practices were classified as representational, 29.6% as representational combined to parametric, 20.4% as parametric, 5.6% as parametric combined to algorithmic, and only 1.9% as algorithmic. In Figure 4, from the total quantitative of the scenario (Pie chart) one has the idea of the expressiveness of the experiments based on the level of computability representational. The systematization developed for this paper explore the criterion of temporal periods, there is a layer of information giving evidence of a process of awareness of the potentialities of the more advanced levels of computability over the last 10 years (Graph in Bars of Figure 4).

Figure 3
Scenario explanation through infographics. In the top: Regional distribution of the institutions with date of implementation. On the bottom left corner: the proportion between private and public institutions. On the bottom right corner: the institution locations proportion between State's capital and other cities.

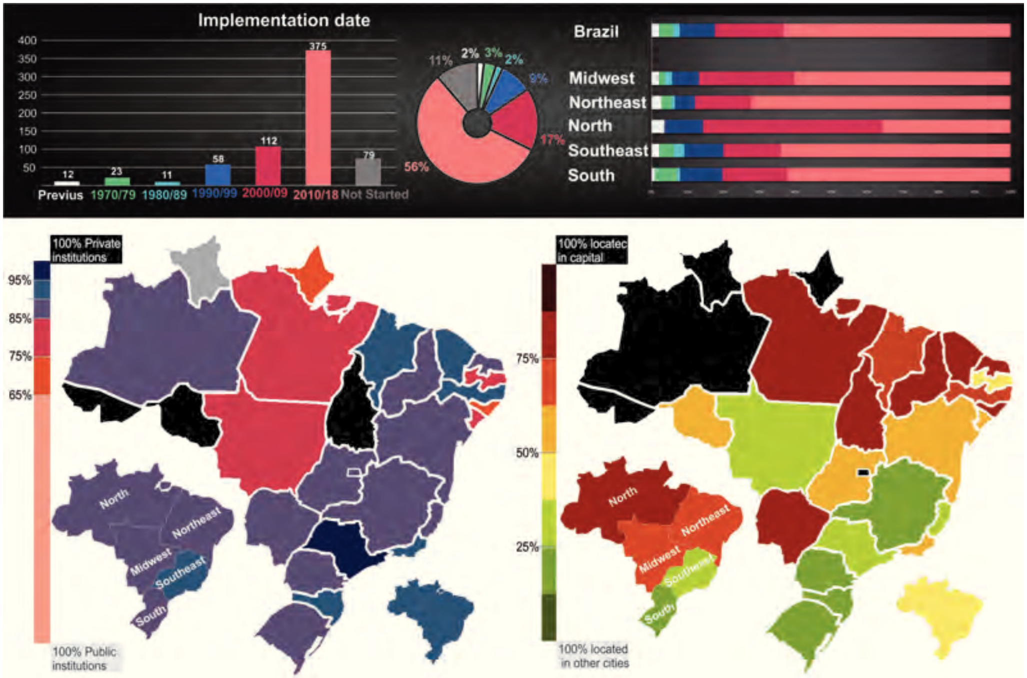
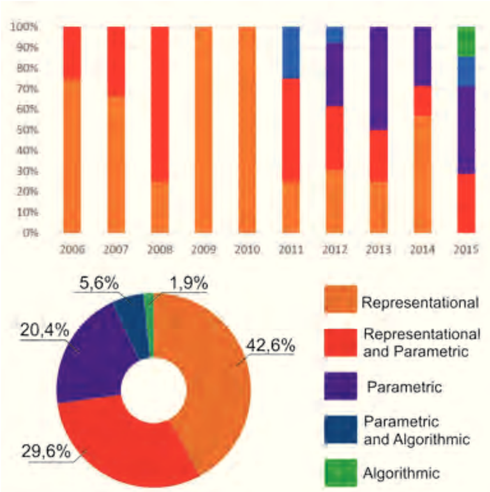


Figure 4
Graphs about teaching practices from the systematization of computability levels, general and temporal data.



Also, it was decided to exclude from the sample the experiments referring to interactions with representational computability level. Therefore, the focus was the understanding of the scenario of teaching practices that explore at least mixed strategies being one of them DAD (Figure 06). The total data (pie chart) show more than half of the DAD experiments are associated with representational processes. However, a transition scenario is identified, in which the incorporation of the DAD into teaching over the years.

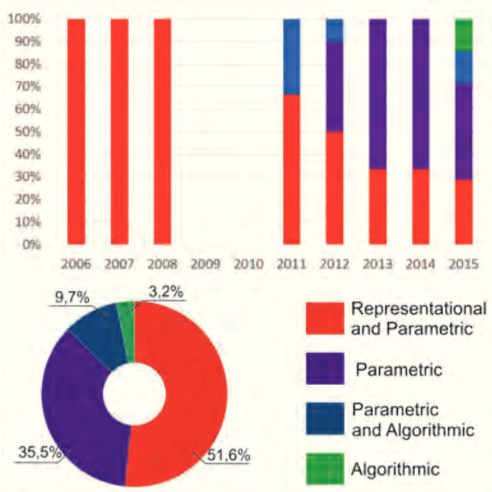


Figure 5
Graphs about teaching practices and computability levels in Brazil (2006-2015) after the exclusion of the representational level

The data information systematized in Figures 4 and 5 were mapped in the territory, placing the teaching strategies according to cities where they were developed. Figure 6a presents all didactic practices in digital environment in Brazil. Figure 6b considers only the experiments in DAD, and excludes didactic practices based on representational level. This graphic shows the localization of the cities and, consequently, more dynamic regions in the production of articles about didactic practices. In the two mappings, it is observed the prevalence of practices in the South and Southeast regions, with some experiments in the Northeast and Midwest.

Considering only experiments in DAD - therefore, excluding teaching practices based in level of computability representational - the more dynamic cities were Campinas and São Paulo with five experiments. Belo Horizonte, Chapecó, Florianópolis, Pelotas and São Carlos showed three to four experiments. Cities that stand out in the scenario with all interactions as Pelotas and São Carlos are observed, however, at the moment that the DAD interactions are analyzed these do not stand out.

Also, in the mapping presented in Figure 6b it was possible to identify cooperation networks for studies carried out in more than one institution. Four papers had didactic experiences that involved a network of institutions in the country and three experiments with international collaboration.

RESULTS AND DISCUSSION

By crossing the institution's mapping with data from previous systematic review, we were able to extract a more realistic view of the situation. The use of computer is widely diffused in Brazil for representation in Architectural Design, and there are a significant number of teachers (some of them researches) dedicated to the subject. However, the didactic experiences developed and reported in undergraduate courses with advanced levels of computability are not representative when compared with the macrostructure of the Brazilian Architecture and Urbanism teaching.

It is observed that most of the research is performed in public universities (70.0%), compared to private universities (30.0%). However, it is important to highlight that there is a different proportion between the number of public and private universities. In Brazil, there is only 57 public institutions compared to 534 privates. Therefore, despite the smaller number of public universities, most of the academic production is originate from these institutions.

Regarding the location of the institution and development of DAD practices, again we find a discrepancy. Analyzing the scenario, 47% of the DAD practices were developed in capital cities, and 53% in inner ones. However, only 39.8% of the institutions are localized in the capital cities. It demonstrates that the universities of the capital cities are implementing a greater number of DAD practices when compared to universities of inner cities. Also, most of courses that presented DAD practices are located in Southeast and South of Brazil (Figure 06).

Figure 6
Mapping teaching strategies in cities of Brazil (2006-2015): (a) Cities of the whole sample according to the number of experiments; (b) Cities according to the number of experiments in DAD with networked experiments.

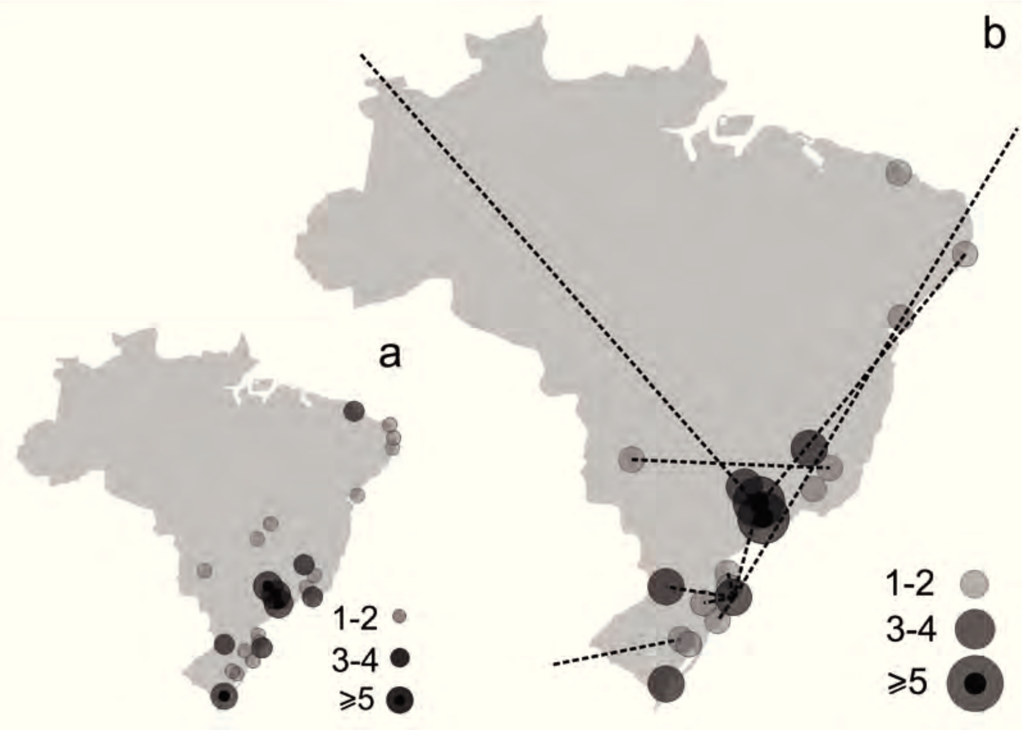


Figure 7
Teaching practice versus Institutions

Moreover, 66.6% of the institution that reported DAD practices were those implemented before the 1980's. Also, it is noted that all the cases with DAD practices where performed in institutions implemented in the last century. On the other hand, from MEC data, 82% of Architecture courses were implemented after 2000.

FINAL CONSIDERATIONS

The relevance of this data crossing to the formal and spatial recognition of the current scenario. Faced to 54 teaching practices from only 27 institutions of a scenario of 591 courses. Also, it was analyzed 30 teaching practices that minimally explore some development in DAD, in 20 institutions.

The study shows how the insertion of DAD in Brazil depends on factors linked to education and research policies. In general terms, public institutions - and sometimes private ones - invest in the initiative between teaching and research in DAD. Most of courses linked to private institutions have targeted the current market suggests with small investment in innovation.

Faced with this scenario that need advanced, we are developing qualitative studies focused in each one of the cases of use of DAD in Brazil, identifying potentialities and limits, in the sense to increase the application of DAD in Brazil.

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Close Future: Co-Design Assistant

How Proactive design paradigm can help

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The present paper is focused on exploring a new paradigm in architectural design process that should raise the bar for a mutual collaboration between humans and digital assistants, able to face challenging problems of XXI century. Such a collaboration will aid design process freeing designer from middle level reasoning tasks, so they could focus on exploring - on the fly - design alternatives at a higher abstraction layer of knowledge. Such an assistant should explore and instantiate as much as possible knowledge structures and their inferences thanks to an extensive use of defaults, demons and agents, combined with its power and ubiquity so that they will be able to mimic behaviour of architectural design human experts. It aims other than to deal with data (1st layer) and simple reasoning tools (2nd layer) to automate design exploring consequences and side effects of design decisions and comparing goals (3rd layer). This assistant will speed up the evaluation of fresh design solutions, will suggest solutions by means of generative systems and will be able of a digital creativity.

Keywords: *Design process paradigm, Architectural design, Design assistant, Agents, Knowledge structures*

SCENARIO

In a changing world - in nature and humans needs - we need very clever tools to speed up the design (Bhatt 2013) - architectural design this case. Architecture as W. Morris [1] stated in "The Prospects of Architecture in Civilisation", a speech delivered at the London Institution on March 10th 1880: "A great subject truly, for it embraces the consideration of the whole external surroundings of the life of man; we cannot escape from it if we would so long as we are part of civilisation, for it means the moulding and altering to human needs of the very face of the earth itself, except in the outermost desert.". More than a century ago W. Morris defined utopianly - but clearly - the vastness of architects' responsibility and now it is dramatically evident. As a matter of facts, humans colonised the Planet and now 7.5 billion people are able to destroy this world as it has been known till now.

It is clear that socio-techno-economical phenomena appear more and more complex and that technological innovation are cause-effect-remedy of subsequent problems. We know that humankind has a steady-acceleration considering it in the whole, but if we considered single phenomenon it would follow the Kondratiev's evolutive curve [2] or modified Kondratiev's wave (Korotayev and Tsirel 2010). The evolution in average of humankind, GDP, technological and science philosophy has had a steady state acceleration. In any kind there was a spiral among problems-resources-side effects-problems and the overall balance has been manageable.

But now in the new era - the *Information Eve* - the curve has had a sharp edge and those concepts have climbed up. Consequences of that huge phenomena have arrived: most world population lives in cities, energy released in the atmosphere increases temperature, pollution is more dangerous that car accidents, and communications - any communication, among humans or things - run more than the capacity to understand context and information itself.

That gives huge responsibility to designers: they should understand in deep problems and boundary critical conditions as they can be able to modify event courses, Planet safety and drive projects toward success or failure (Meadows 1972, Diamonds 2011).

To manage these extreme problems and conflicting solutions means "designing". In our CAAD world, we should adhere to strategies nature did, particularly one of most successful example of adaptation: the human behaviour.

What humans do? Optimise. Optimizing thinking especially.

They are able to selectively explore solution domain. They are able to take into account any constraint and to skim off the wrong ones or not well-suited solutions.

In a design process, designers have to figure out predictions by means of simulation/learning tools that now are able to crunch a behemoth of numbers. But these examples are related to *brute force* + mental short-circuits as they are thought for "fewer dynamic domains with fixed rules in a limited period of time" compared with the Architecture-related knowledge domains.

Architecture, in a broad sense, is quite different from other discipline as their artefacts are unique or and rooted. So, it must be considered at the same time: artistic aspects, building sciences, economical matters, social impacts. It has a peculiarity that it takes into account very long time period problems, but codes and regulations change very frequently as well as market rules, building components and new materials.

In Architecture to manage such a bigger complexity (just for instance: ancient building restorations, urban zone renovations or high performative buildings) the process has been subdivided into phases and in specialists' works, so useful tools have been developed so far that follow the standard process of defining phase by phase solutions.

BACKGROUND

In recent decades relevant organizational efforts have been made in design process knowledge management by means of initiatives based on advanced information and communication technologies (ICT). However, organisations have experienced that leveraging knowledge through ICTs is often hard to achieve.

Walsham (2001) addressed the question of why this is the case, and what we can learn of value to the future practice of (design process) knowledge management. His analysis is based on a human-centred view of knowledge, emphasising the deep tacit knowledge which underpins human thought and action, and the complex sense-reading and sense-giving processes which human beings carry out in communicating each other and 'sharing' knowledge.

Looking specifically at the CAAD context, we concluded that computer-based systems can be of benefit in knowledge-based activities, but only if we are careful in using such systems to support the development and communication of human meaning and intentions (Trento et al. 2016, Novembri et al. 2017, Trento et al. 2018).

Architectural design process problems can be subdivided in two parts: the first one, it is the intrinsic nature of design process and how it can be faced by a new model; the second one, how such a model can be defined by an applications ecosystem (a Digital Assistant) to be built upon it.

Regarding the first point, designers and researchers to deal with these tasks extensively explored the "Collaborative design" process paradigm as it can overcame the "Traditional design" process weaknesses where the activities were rigidly subdivided in boxes and each designer specialist operates inside his/her own box. Very often the latter process leaded to inconsistent solutions, organizations had partial overlapping competencies, so some part of problems are not dealt with by any specialist and the pyramidal hierarchy was so high that decision process was very slow.

Collaborative design paradigm studies (Kvan 2000, Achten and Beetz 2009, Fioravanti et al. 2011) turned out that to be effective the design process should have had been overcome among many problems: inconsistent data and incoherent semantic entities. The former has been faced by means of a "BIM (tool) layer", the latter by means of an Ontology representation - OWL). So that it has been added a new layer over the BIM layer, the so called "upper Ontology layer" (Carrara et al. 2017).

Consequence of that it was needed a "bridge" of relationships between the "BIM layer" and the "upper Ontology layer", this goal has been tackled by many approaches and solutions according to: J. Beetz, J. P. van Leeuwen and B. de Vries (2006); A. Fioravanti and G. Loffreda (2015); D. Simeone, S. Cursi and M. Acierno (2019); A. Fioravanti, G. Novembri and F. Rossini (2017).

The inconsistent database management problem has been treated by J. Gray - the Google Earth inventor - and now it is no more a taboo to deal with inconsistent entities, f.e. different interpretations of archaeological site entities (Cursi et al. 2015) or putting together ontologies and shape grammars (de Klerk and Beirao 2016).

We already explored in a previous study the possibility to realize a partial proactive design tool (Carrara et al. 2012), but with traditional ontologies it is possible to treat only entity property incoherencies (2nd layer). As a matter of facts those ontologies are not able to treat difficult-to-classify entities, for instance different percentages of datings and interpretations of the same entity by an archaeologist (for example a capitol fragment embedded in a ruin), nor deep reasoning, which both take place at the 3rd layer.

CHALLENGES & NOVELTY

The goal to be pursued is a new design process paradigm that makes designers to face - in an easier way - complex problems as those cited before.

So, going back to thinking optimization and paraphrasing John Archea (1987), "what -*great*- architects do?".

Apart the shortcomings of software programs and deficiencies in methodologies described in previous sections, from scratch they concurrently think at different abstraction layers and take into consideration different partial solutions of different design phases. They have in common that they sketch on a sheet of paper drafts that represent a building overall shape beside a vault detail, an interior perspective and the brick they prefer (Carrara et al. eCAADe 2004).

If they change an element, all their own reasoning networks in their brain will be activated - in real time - as far as it is possible.

Another problem to be tackled if we modelled the architectural design process with OOP entities, would be the "combinatorial explosion" of entity attributes (i.e. other entities) we have to define (Tessier et al. 2001); it is not just a quantitative problem related to the huge attribute number but the ability to address information in a synthetic way that means an upper knowledge abstraction layer. That it is not tractable with usual ontology systems as f.e. Protégé Ontology Editor (Musen 2015).

So, we need an "application ecosystem" - an *Assistant* - able to take into account heterogeneous entities of different knowledge abstraction layers (each of these ones with several levels of detail) in domains full of default entities, that in real time explores entity networks and puts in evidence consequences and side effects.

Summing up all these characteristics we can define a model of abstraction layer that can act as a *proactive design assistant*.

METHODOLOGY

We already studied the first two layers: data layer and simple reasoning layer (Predicate Logic) together with a new 'bridge' between them (Fioravanti et al. 2017). Now it is time to think about the 3rd layer, the one of strategic thinking.

Design "entity" history in short from computer science point of view:

- First - digital OO entities - they belonged from an ontology universe made by objects; these objects had inheritance and automatic propagation of consequences; only one world = geometry and included knowledge.
- Then - digital entities are "pluri-objects" - they belonged from many ontology universes thanks to ontological representations; a dual representation world = geometry and knowledge for each specialist actor.
- Next - digital proactive entities - they belonged from many ontology universes and are represented by agents, agencies and actors; all the worlds are made by them (Mei, 2015).

The third layer can be done by means of a network of mixed knots of agents, ontologies and fuzzy ontologies and should be explored a possible cooperation between stochastic and deterministic searches.

What we want to highlight is the need to do not limit the present research on CAAD systems "only" to the development of 'intelligent' routine that can help designers to design faster, memorize and manage big data or produce increasingly realistic simulations.Proactive design assistants should rather explore and enhance the responsiveness based on the cognizance of complex relationships that exist between professional knowledge, to activate them, exchange them and increase them in the life cycle of the "*aedificium*".

To support proactively designers, third generation of CAAD systems should be able to perform the following complex tasks:

- To define, by means of a satisficing approach, the designers' objective;
- To enhance awareness about the design product/process, in relation to the designer objective;
- To compare goals and explore consequences and side effects of design choices (3rd layer);
- To reach the designer at the right moment with the right contents: evaluation and prediction.

In a proactive design process the assistant will automate a fast evaluation of fresh design solutions, will suggest solutions by means of generative systems and will be able to perform a digital creativity (Colton and Wiggins 2012).

CONCLUSIONS

From the clients to the designers, from the builders to the end users, the state of the art related to the tools for the management of technical knowledge and to handle architectural design process has been studied in depth and a new paradigm has been delineated in order to capitalize on the enormous amount of knowledge of which they are protagonists (producers-consumers).

If the various actors, especially in the initial stages of planning and engineering, will be aided by proactive design assistant, the quality of the buildings and of the lives of those who live there can only benefit from them.

We argue that CAAD systems need to support the use of information for action, but that this is often compromised by poor quality and reliability of data. In addition, good data and related design-oriented ICTs are inadequate by themselves since effective action also needs knowledgeable people and supportive institutions.

What we want to underline is that new approaches must be discussed on CAAD software philosophy, educating people and changing institutions. We need an effort to conceive an all new paradigm as theory and practice in design have never been so intertwined as in the last years.

This is a theoretical effort to treat design process problems as a whole, related to Architecture complexity that after almost fifty years from Architectural Machine (Llach 2011) seems possible to be faced.

ACKNOWLEDGEMENTS

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[2] https://en.wikipedia.org/wiki/Kondratiev_wave

Matter - FABRICATION AND CONSTRUCTION 1

Mass Customization of Deployable Origami-based Structures

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In this research we present a design for a mass customization online 3D model for deployable emergency shelter that automatically provides drawings for CNC machines. The main motivation for such research has risen from a global need to provide emergency shelters for people affected by natural disaster. The model is designed to be a flat packable, mono-material based on a double corrugated folding pattern. Based on numerous functional, structural and fabrication constraints the presented model can provide a myriad of similar geometric forms that can reflect personal needs and can be used for different purposes.

Keywords: *Mass customization , folding pattern, digital fabrication, emergency shelters*

INTRODUCTION

Origami patterns have been used in the process of architectural design for many decades. Due to the applicability of paper models in design experiments as well as load-carrying capability of certain folding patterns, origami inspired folding structures have been widely applied to the design of architectural structures (Buri, and Weinand 2008; Šekularac et al, 2012; Tao Shen and Nagai 2017). Recently, advances in computational design fostered extensive research on the application of origami-based structures in architectural design (Buri and Weinand 2008), construction (Tromer and Krupna 2006), energy efficient design (Martinez-Martin and Thrall 2014) and manufacturing (Robeller and Weinand. 2016a; Robeller and Weinand. 2016b). Additionally, many societal challenges as well as sustainable approaches to design affect the increasing interest towards transformable folding structures. As opposed to conventional static, structurally stable origami-based structures, deployable structures have the capacity to efficiently respond to different boundary conditions, environmental and climatic conditions, functional requirements, or emergency situations (Temmerman et al. 2014).

In this research we present an open model for mass customization of a deployable origami-based structure. While current research of deployable origami-based structures is mainly focused on its geometry (Demaine and Tachi, 2017; Cai, Deng, Xu and Feng 2015) or structural behaviour (Chudoba, van der Woerd, and Hegger 2014; Lee and Gattas, 2016), we investigate how advantages of such structures can be used for mass-customization for real-world situations through the application of an online configurable model. The main motivation for such research has risen from a global need to provide emergency shelters for people affected by natural disaster. We have designed a mass customization online configurable 3D model for deployable emergency shelters that can automatically provide a myriad of similar geometric forms, based on predefined design, functional and construction constraints.

This research has been motivated by the international workshop held at the University of Novi Sad, organized under the framework of United Impact Academic Program, Green Contributor organization (Canada), BNCA School of Architecture, (Pune, India) and Digital Design Center, Faculty of Technical Sciences, University of Novi Sad. The aim of the workshop was to design and create simple flat packable and floatable emergency shelters which could withstand the pressure during natural disasters, including floods.

METHOD

The mass customized model presented in this paper is based on the geometry of a reverse folded pattern (Buri and Weinand 2008), also known as double corrugated [Mitra 2009] or the rigid-foldable accordion pattern (Lee and Gattas, 2016). All models are designed to be flat packable, which means that they are made from flat material sheets. The three dimensional structures based on origami folding can be unfolded for the purpose of storage or transport which adds to the efficiency and applicability of the origami-based design. The design process is created in a parametric environment, which allows adjustment of the shape and size to the personal needs of anyone who uses the model configurator. The size and shape of the shelters as well as the distribution of openings are also stored in an online parametric model, allowing the user to automatically create the drawing for CNC machining according to their own need. While design and construction of emergency shelters are often considered for serial production, the presented mass customization tool enables user participation and a variety of design solutions with a low unit cost associated with mass production. CNC machines are used to create kerfs on the material which represent the folding lines. This allows the material to be easily folded in providing emergency shelter or unfolded to the flat panel according to the current needs.

The creation of a mass customization tool that automatically generates the drawings for CNC milling consists of 4 phases: 1) design of the parametric model based on the geometry of a reverse folded pattern, 2) design of an online configurable model based on the parametric model, 3) material tests with mock-ups, 4) digital fabrication of the prototype.

Design of the Parametric Model

In order to provide a suitable digital environment for the design of the parametric model, Rhinoceros 3D with its graphical algorithm editor Grasshopper is used. The model is completely based on a parametric algorithm, which means that there is no need for manual 3D modelling. The 3D model of origami-based shelter and unfolded model are generated automatically and the shape of the shelter is adjustable with parameter settings. The shape is defined by the closed outline which represents the cross section of the foldable structure and the angles which determine the corrugation of a double corrugated origami pattern in a longitudinal direction (Figure 1). The shape of the outline and the angles are controlled by the configurator.

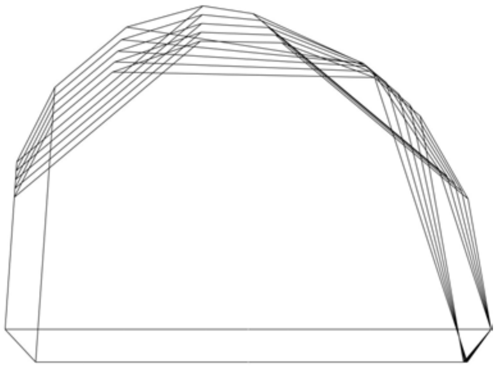


Figure 1
Example of cross section shape variation controlled by a configurator parameter

The first step towards the model design is creating a cross section outline. The outline is closed due to the project requirements for the structure to be floatable and stable without anchoring. The outline is a polygonal line which has an even number of vertices. The number of vertices is important because each pair of neighbouring lines uses a different fold an inside and outside reverse fold. The fold changes from the inside fold to an outside fold and vice versa in each vertex.

Since the outline is closed, the even number of vertices is necessary in order to make a tunnel like reverse folded, closed structure. The outline starts with the horizontal line which is necessary because it represents the cross section of the floor of the structure. The shape of the outline is further specified by the parameters which determine the angles and the lengths for the rest of the lines. These parameters are adjustable by the user in a way that allows for the control of the resulting shape. The model is made to restrict the maximum perimeter of the polygon to be less than 3000mm because the unfolded structure has to fit in the single sheet of material of that width. Additionally, the sum of polygon exterior angles is 360° and the size of the angles are limited within the range defined by the perimeter of the polygon (Figure 2).

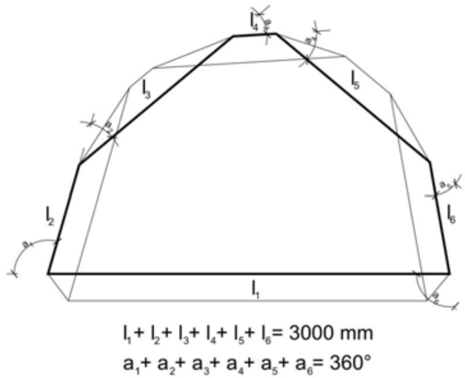


Figure 2
Geometry Constraints for the Cross Section Outline

When the cross section outline is defined it is used to model the position of the ribs at each linear part of the outline. The slope of the ribs, defining the fold angle can also be controlled by the user.

After the slopes of a single rib for each line is defined, the ribs are multiplied creating the corrugated origami-based tree dimensional structure. The total number of ribs can be selected by the user. However, the parameter which controls the number of ribs is constrained to a set maximal length of the unfolded structure to be less than 1500mm in order to fit in one sheet of the material of that length.

When all the parameters are set the origami-based three dimensional structures are created. The structure's unfolding mechanism is also automatized. That means that the user defines what he desires to create a 3D and technical 2D drawing of an unfolded structure (which can be directly used for CNC cutting) and is automatically generated according to the parameters entered.

Design of an Online Configurable Model

After the parameters and workflow for the model are designed, an online configurable model based on the parametric model is created. The model is exported online by the ShapeDiver add-on for Grasshopper3D. Anonline environment for this parametric model allows a wider audience to easily approach the configurators and use the algorithm. Users that want to design and fabricate their own emergency shelter need only a smartphone and internet connection to do it. The advantage of such a configurator is that no special CAD or 3D modelling software has to be installed on the computer and no previous knowledge about 3D modelling or parametric modelling is required in order to send necessary inputs to the CNC machine and manufacturer. In addition the online configurator has only controllable parameters and the viewport showing the 3D model and unfolded pattern which is generated according to these parameters. Likewise the shape parameters are constrained to ensure that the 2D unfold can fit a single sheet of material. Then the export button enables sending a dwg file format ready for the milling process. This process of parametric modelling of the tree dimensional structure and unfolding of the structure is done in the background. The application of ShapeDiver add-on enables an iframe embedding link that can be copy -pasted directly in any

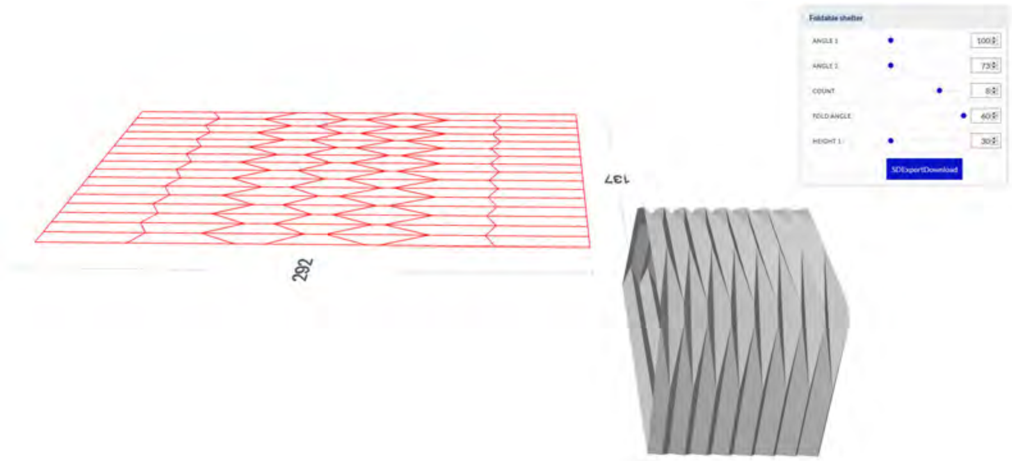


Figure 3
Interface Design of Parametric 3d Configurator for the Emergency Shelter

webpage. Additional options including managing a camera or light sources in a 3D scene is accessible through ShapeDiver's API, which is based on Tree.js WebGL based library. The online model presented in this work (Figure 3) can be accessed on the following link: www.arhns.uns.ac.rs/cdd/foldable-shelters

Material Tests with Mock-ups

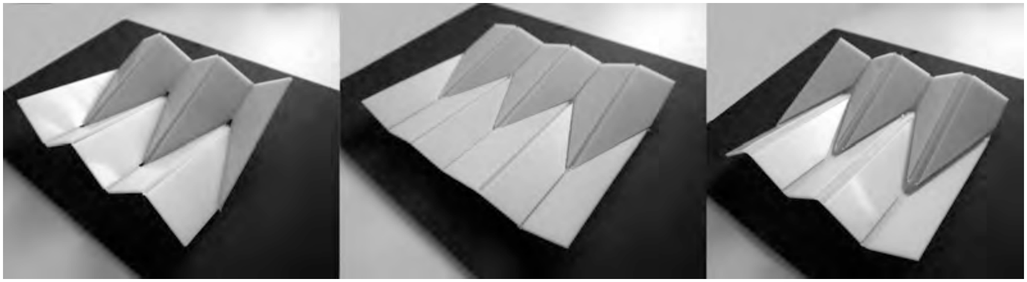
The material tests with the mock-ups are made in order to test the foldability, which means finding a suitable thickness of the material, as well as the width and depth of the kerf. Apart from the common material applied for emergency shelters that utilize corrugated cardboard or fabric, for this research a polyethylene PE-500 3 mm thick sheet was used. PE-500 is a material with good physical and mechanical properties for creating mono-material deployable shelters. PE-500 is a non-hygroscopic environmentally friendly material, which exhibits high impact resistance and excellent machinability. A good combination of stiffness and toughness enables the PE-500 material sheets to fold multiple times along the kerfs without fracturing. For testing foldability of PE-500 sheets, we folded mock-ups 20 times from the unfolded planar stage, to the maximum folding position. Due to the high level of material toughness PE-500 sheet mock-ups showed that it can be used multiple times without cracks.

We made tests on 3 mock-ups to find a suitable kerf width, depth and orientation (Figure 4). We started with the presumption that the material had to be kerfed from both front and back side, in order to enable reverse folding easy. However, kerfing on both sides of the material created holes in the places of intersection on both frontside and backside kerf lines (Figure 4 left). For this reason we created two additional tests with kerf lines only on one side of the material to find an optimal kerf size and concluded that 2.3mm deep kerfs are suitable for fabrication on 3mm thick PE-500 sheets (Figure 4 middle). Additionally, kerf width of 10 mm is suitable comparing to depth because it is large enough to enable 180° folding without weakening the material (Figure 4 right).

Digital fabrication of the Prototype

The dimension of the polyethylene PE - 500 sheet we used was 3000x1500mmm and the prototype was manufactured in a 1:2 scale. The size of the shelter can be larger if the larger sheet is used or if the two or more sheets are connected. Polyethylene sheets

Figure 4
Material Tests with Mock-Ups



can be connected with a puzzle joint connection or by welding process. This puzzle joint connection is based on friction-fit assembly logic which can provide making large structures at low unit cost from small sheets of the material without any additional tools or adhesives (Tepavčević et al 2017; Sass and Botha 2006). Similar properties of the material and kerfing can be used for the full scale emergency shelter prototype.

Kerfs are made by using a CNC milling machine. Since the kerfs allow 180° folding, the prototype can be folded by any fold angle during the assembly without the risk of material breaking. This is important because it would be impossible to fold the material only up to a particular angle during the assembly. For each shelter one piece of the material was used, so there was no stitching of the material during the assembly, only folding (Figure 5). When folded, the prototype had to be glued only on the upper side to create a continuous structure.

DISCUSSION

In this research we focused on the process of creating a mass customization model which can be used in the design-to-fabrication process for deployable origami-based emergency shelters. Compared to existing solutions, we decided to focus on creating emergency shelters that can be personalized through a mass customization process and yet cost-efficient, easy to use, pack or transport. In order to satisfy all this criteria we focused on mono-material folding solutions. The geometry of a reverse folded pattern used in the creation of this parametric model has many advantages in the context of their use as emergency shelters. A cross-section of the shape is a closed polygon generating a structurally stable origami-based structure.

A reverse folded pattern configuration consists of planar trapezoids. Compared to the triangular structure, it has only four planes that intersects at one common intersection point. Due to the lower number of planes that intersects at a common point, the assembly process is much easier.

Many origami-based emergency shelters are manufactured with cardboard material [1,2]. Cardboard origami shelters are also a sustainable and compact mono-material shelter as the presented one, based on PE-500. However, cardboard shelters need waterproof coating in case of its usage against the rain. Resistance of waterproof coating is not fully reliable in cases of devastating monsoon floods. Using a polyethylene PE-500 not only provides protection from rain, but can also provide a design based on buoyancy principles.

Finally, we show that design of such a structure can be distributed to end users with a web page link, providing instant design as well as variability and adjustability to the specific needs and number of users.

Figure 5
Folding Process

Figure 6
Buoyancy Test

CONCLUSION

The mass customisation model shows that due to numerous functional, structural and fabrication constraints, the origami patterns based on reverse folding provide a solid base for creating a myriad of forms for shelters that can reflect personal needs and be used for different purposes. An origami based design made only by folding from a single piece of flat material used in this paper demonstrates that it is possible to create the tree dimensional structure that can be easily folded and unfolded depending on current need. This is an important benefit for an emergency shelter which is a temporary structure since it can be efficiently stored and easily transported onsite.

The mass customisation tools are useful if they are available to a broad audience. Transferring the 3D parametric model to an online platform in order to generate the model and cutting scheme for a CNC machine demonstrates the full potential of mass customization.

ACKNOWLEDGEMENTS

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Digital Housing

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This paper exposes some of the experiments and results attained in a broader research project carried along in our University.The research is focused on the development of a wiki-like house building system, derived from preceding cases.It goes space from layout generation through full-scale prototyping of a new system and it's intended to further reduce construction costs while retaining some flexibility in space layout and dealing with consequent variations in construction components.

Keywords: *Digital Housing, Fabrication, Prototyping, Wiki-House*

INTRODUCTION

Digital Housing research is part of a broader effort to acquire and develop digital technologies in a developing country context. The main goal is to acquire, analyze, redesign and program a complete housing construction system, derived from but not constrained to the WikiHouse concept. The project is specifically tailored to Brazil's economic and technological reality.In the Wikihouse community, a philosophical - ideological principle seems to underlay the majority of the initiatives. Wikihouse is presented as a system that decentralizes and distributes knowledge in the form of a pre-programmed construction package. Wikihouse.cc website states as their mission: "1. To put the design solutions for building low-cost, low-energy, high-performance homes into the hands of every citizen and business on earth.2. To use digitization to make it easier for existing industries to design, invest-in, manufacture and assemble better, more sustainable, more affordable homes for more people.3. To grow a new, distributed housing industry, comprising many citizens, communities and small businesses developing homes and neighborhoods for themselves, reducing our dependence on top-down, debt-heavy mass housing systems." (Wikihouse.cc, 2018)At first, those principles would easily meet the requisites defining Industry 4.0, that is, Interconnection, Information Transparency, Technical assistance, Decentralized decisions.It so happens that in developing countries those requisites are far away from reality, at least in cities and regions removed from the biggest economic centers.Most experiments carried in research centers and universities in Latin America rely on digital infrastructure present in those centers, and so is our research. This research thus encompasses the study and production of a complete CNC machined construction system ready for delivery and assembly in construction sites. Main topics of research are: Wiki-like systems comparisonComponentized construction logicsParametric and constraint-based designSystem redesign for greater economy in developing countries.This article focuses specifically on the Digital Housing parametric and constraint-based aspects of the research.

METHODS

The complete research comprises the following aspects: 1.Wiki-like systems comparison: Our research has focused on the understanding of three different wiki-like systems.2. Componentized construction logic. The study has focused on understanding the principles of modular coordination in wood framing construction and its application in wiki-like systems. 3. Parametric and constraint-based design. Departing from previous studies in parametric and constraint-based design, the study seeks to deliver a programmed system for the generation of wiki-like design variations.4. System redesign for greater economy in developing countries. Parallel to that, the research intends to attain greater economy in material use while granting reasonable energetic and structural efficiencies.

PRECEDENTS

Literature with a specific focus in wikihouse and similar fabrication systems is scarce and usually very shallow. Lawrence Sass seems to have the most consistent bibliographic production on the subject, mainly related to his research on the Instant House. Sass's papers don't expose much of the system's construction details. On the other hand, its Shape Grammar approach to systematize construction logic is unique, deriving from other authors' Shape Grammar studies.

Wikihouse foundation is somehow more centered in the social aspects and its website has a clear emphasis on the description of the wiki construction system and strategies related to it. In Wikihouse construction logic is embedded - although not in its full extents - into the WREM system, currently developed in Rhino - Grasshopper. A rather important experiment was also carried out in Rio de Janeiro, at Universidade Federal do Rio de Janeiro, led by Clarisse Rohde in 2015.

FACIT (London - Bell Travers Willson, 2007) adopts the same principles Wikihouse and the Instant House: precut CNC machining of panels from a digital project where fittings are precut. The main difference in FACIT's system components is its pre-assembled "cassettes" which are interconnected in-situ. It might be added that FACIT was developed into a full commercial fabrication system and is now a fledgling architectural business. The FACIT prototype was not compared to the other three systems in this research.

ClipHut, an initiative at Ostwestfalen-Lippe University of Applied Sciences, adopts the same CNC pre-machined components logics, but instead of plywood, it adopts OSB panels for the structure cassettes. Those systems are being studied in a rather systematic way. Each one has been redrawn in CAD - 2d and 3d and then reprogrammed in Grasshopper. From the Grasshopper parametric definition, scale models in 1/3 and 1/6 scales are generated, machined and mounted.

Each studied system is then examined against a series of checkpoints, the principal ones being the joint system logic, degree of complexity in machining patterns, cassettes' structural soundness, ease of assembly.In the ideological realm, the study is influenced by an urge to make the system more participatory, in the sense conveyed in "[...] that design in collaboration is not only associated with the Seventies, but that this is a modern, even postmodern notion which provides us with the basis for both social and scientific development in design theory." (Bax, 1995)

The final design for the research group Housing Project comprises the redesign of the whole system from the ground up. Main goals are: Substantial reduction in material consumption while retaining structural soundness. Substantial reduction in joint machining and thus a reduction in machining time, Coordination between the componentized system and more traditional dry construction materials and methods.

EXPERIMENTS

In order to coherently coordinate fabricated components into a constructive grid, software needs some control over plain boards dimensions and a sound structural spacing between structural cassettes. A completely constrained system would, in fact, permit an extremely great number of plan variables. On the other hand, a less constrained system can accommodate for a broader range of finish panel dimensions, flexibility necessary for an uneven market such as Brazil. This has led the team to adjust grasshopper programming to simultaneously allow for closed systems - modularity and joints logic - and adaptability to variations in panel dimensions. As for modularity control, the research established an array of possible interconnections among partitions related to a constructive grid, in what Shawcross describes as a "Severely Constrained Design" (Shawcross, 2013)

The team has worked with Wikihouse Wren 4.1 and 4.2 as the base system for testing and results comparison, since it's the best documented and more widespread, making access to other experimentations more secure. However, we've also reverse engineered Lawrence Sass' Instant House and prototyped samples in ⊠ in order to assess its capabilities and learn from it.

More recently the team also reverse engineered the ClipHut system - from their website pictures and description only - and is beginning to assess its potentials. The most interesting point in the ClipHut model is its use of OSB, while all others use plywood. Also, ClipHut doesn't employ the cassette concept, adopting a rather simpler system akin to traditional wood framing systems and relying entirely on a 'clipping' system for fast assemblage.

Space Allocation and Volume Generation

Experimentation departed from a preliminary architectural program that would meet the requirements of the Brazilian Social Housing Program - PMCMV - , adapting them to the lot and the growth criteria. However, the resulting minimum footage is 54 m2 of constructed area, higher than the minimum proposed by PMCMV.

Once the characteristics of the architecture and growth orientation were defined, a maximum number of possible dwellers was established, considering the lot size, the growth of the architecture along a single axis and the maximum number of four beds per room. Given the size of the lots and the option for single-family houses, the maximum number of residents was limited to eight, considering that the living room should expand to the limit of a sofa for eight people and the kitchen for a table of up to eight places. Although the minimum room accommodates up to two people, it might receive only one person, impacting the sizing of the other rooms. Thus, supposing a house of three bedrooms to eight people, one of which would house a single person, the others will have to house three and four people. The dialogue with future residents is based on an algorithm developed in Python language, which will ask questions and, depending on the answers, will offer more options, defining the characteristics of the architecture.

A series of questions are proposed to a hypothetical user, from which numerical data is derived and fed into a Python script. Data is then fed into Grasshopper, where plans and volumes and generated.

Figure 1
Grasshopper screen capture: script to generate Plans and Massings from Python code

Figure 2
Grasshopper Screen capture: Plan for a 4 occupants dwelling.

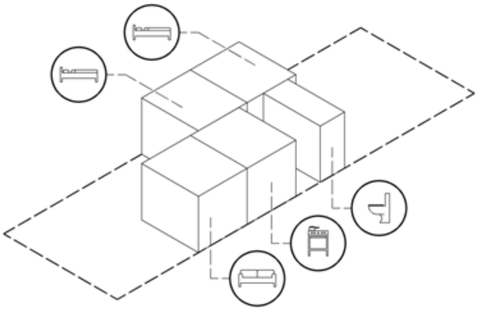


Figure 3
Rhinoceros Screen Capture: Volume generation from a Plan variation for 4 occupants.

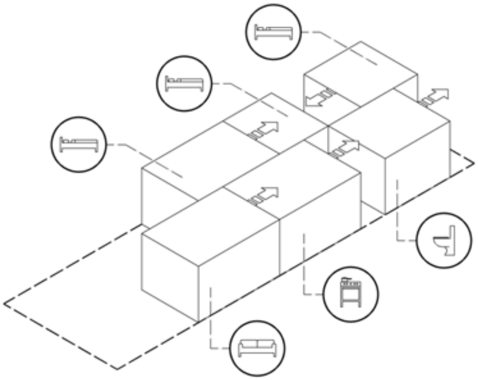


Figure 4
Rhinoceros Screen Capture: Volume for an eight occupants dwelling.

Shop drawings generation

The connection between the Space Planning module to the Component Design and Fabrication phase might be done in two different ways. Either a series of section lines can be generated directly from Rhinoceros geometry, or the Grasshopper geometry can be fed directly into the Components module. The first one is being used for the ease of operation and because glitches in grasshopper processing large amount of information will not disrupt the work.

Once the transposition from the Massing Model to the porticated structure design model is performed, a series of Grasshopper scripts are employed to parametrically produce shop drawings for CNC machining.

In previous experiments and during the comparison of different wiki systems, testings were carried out to evaluate the performance of all the compared systems and the one being proposed. Machining speed, ease of assembly and structural soundness were accessed.In special, structural soundness for the system behavior using 9mm OSB was a key factor, as related in a Paper in SIGraDi 2018.

A 1/3 scale model, laser cut from MDF 3mm panels was built, for proof of concept.

During the construction, adjustments in the tonge and groove fittings were made and incorporated into the design. Claddings and other fittings such as doors and windows were modeled in 1/3 and assembled into the model.

As a general method, many adjustments were first designed in Autocad 3d and 2d, and latter coded into the Grasshopper script. This allowed the team to cope rapidly with assemblage problems and to keep the construction pace. Ideally, the scripts should have been edited in the first place, but the team found that disruption in the assemblage was the main issue to be avoided.

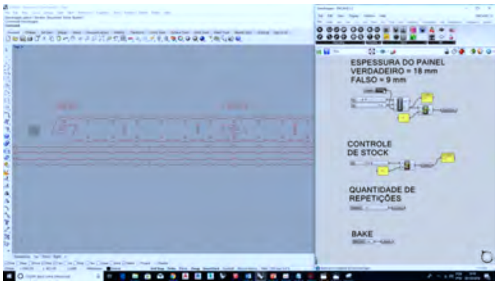
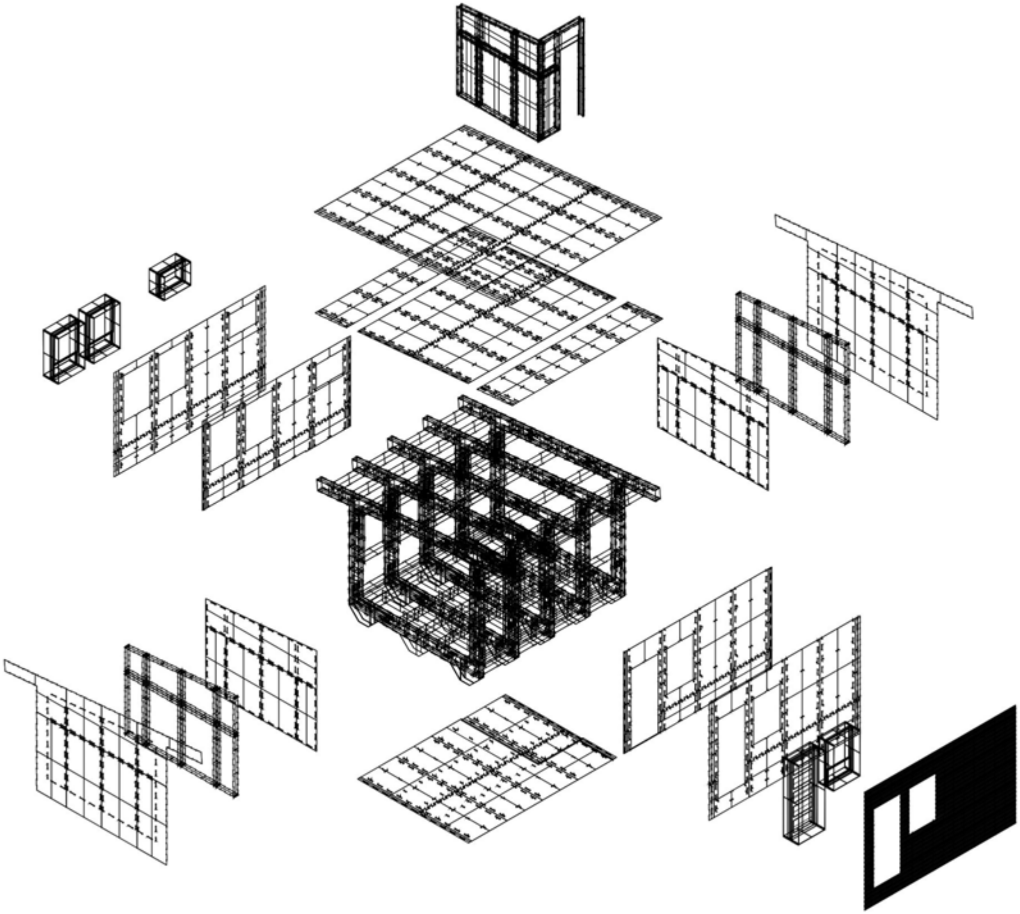


Figure 5
Grasshopper Screen Capture: scripted generation of the portico segments for fabrication. Variation in stock, machining tolerances, length of segments are set according to modular controls.

Scripting validation was thus attained by the superimposition of the Grasshopper generated designs onto the Autocad drawings.

Figure 6
Exploded view of the complete system



RESULTS

Plan and Massing generation

Digital Housing programming tasks have reached the following stages so far:

1. Modularity Control User input dependent. Upon selection of boards dimensions - both for the structural system and the cladding systems -, a constraint system limits maximum and minimum spacings. Modularity Control feeds both the 2. Plan Generation module and the 3. Volume Generation Module. Bidirectional control is not possible in the system (which is merely a scripting system in Grasshopper, not allowing for iterations).
2. Plan Generation - User input dependent, meaning that presently we have not reached full automation in space allocation and arrangement. The system is under continuous development and will ultimately be presented with a web interface, allowing users to access main parameters to guide plan generation and choice of materials.
3. Volume Generation: User input dependent after 2. Plan Generation.
4. Parts generation: Automated. All parts are derived directly from the 3. Volume Generation module and constrained by the 1. Modularity Control module

Components generation and fabrication

From the Mass Model in phase 1, parallel section lines spaced accordingly to the construction module are subdivided in Grasshopper and used as a basis for the parametrically generated component design.

Preliminary prototypes in ⊠ scale have mostly been generated through the programmed modules, but the modules don’t communicate seamlessly yet. Adjustments in the flow of information from one module to the next were studied in this phase, resulting in simpler and faster scripts.

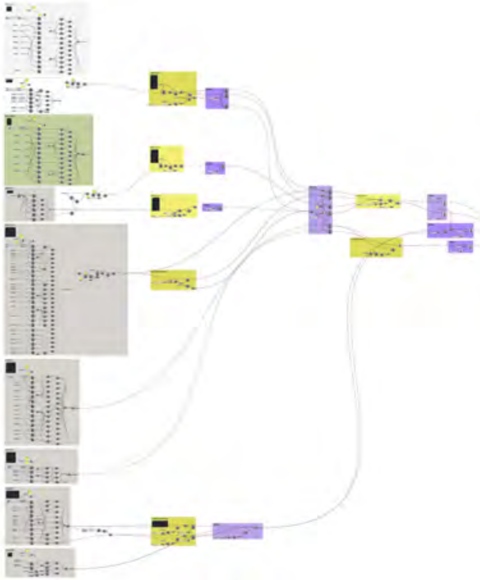


Figure 7
Complete code for the system - Grasshopper screen capture

The main prototype before the 1/1 scale model was the 1/3 model, entirely laser cut. This is regarded as our final proof of concept since the majority of the adjustments in the joint systems are tested and adjusted in this scale. Minor adjustments are expected to happen in 1/1 scale. By then, all adjustment systems will be scripted in Grasshopper, allowing for a fast-paced production rate.

Figure 8
1/3 Scale Prototype cut in 3mm MDF boards, Assembly

Structural behaviour tests

A series of structural essays were performed in order to access whether 9mm OSB panels would be an acceptable choice for construction, thus ensuring that one of the main goals in this research was met: lower material consumption and lower overall construction cost.

Overall results show that 9mm OSB is an entirely acceptable solution.

DISCUSSION

Plan and Massing generation

This research has not gone deeper regarding space layout generation. Presently the code 'embeds' alternatives for layout generation, this meaning that all possible options are 'precoded' into the Grasshopper script.

As such, any new space layout or formal solution should be added by new lines of code. Further exploring space layout generation is not, at the present moment, considered to be a viable solution in this research.

Fabrication System

Former balloon-frame and the current platform-frame construction systems are in the origins of most modern CNC machined systems. Possibly the single most important argued difference is that in Wiki-like systems the whole of construction logic comes embedded in the components, while light framing systems need insitu, qualified workers. However, for a complete working model, many 'non-programmed' operations are still needed to complete a housing project.

Dry construction strategies have taken a long time to occupy significant niches in developing countries such as Brazil, mainly because they rely on industrial plants for mass production of components, but also because mass walls and post and beam concrete systems have dominated both the construction market and, as such, the whole architectural education scene. The architecture education culture thus evolved on the basis of 'open systems', i.e. construction systems not constrained by modularity or prefabricated systems.

The dominance of in Situ concrete pouring into handmade formwork and CMU/plaster have precluded obvious advances such as modular coordination, prefabricated and componentized construction to very small niches in Brazil.

Considering sustainability issues, while the adoption of OSB seems to be a good economic choice, since its raw prices are less than 50% that of plywood, it should be noted that it poses a problem since "when contrasting OSB with plywood on the basis of sustainability, plywood is a more sustainable structural panel product between the two. [...] production of plywood utilizes lower energy and generates fewer air pollutant emissions of CO2, SOx, NOx, VOC, and particulate matter." (Chan, 2012)

A study on 'wiki' systems responds to both the immediate need to accelerate housing construction where there's a lack of skilled labor and to gain territory in the architectural education realm, as this project is being done in the University research facilities.

However, the idea of 'programming' construction logic into a 'wiki' system goes in the opposite direction of really empowering local labor with more sophisticated skills. This has been a general trend in the Digital Era: knowledge is embedded in programs and/or programmed objects. From a rather shallow viewpoint, this appears to be to the advantage of poorer populations. However, these populations might as well continue to be set apart from knowledge production and thus not empowered at all.

In developing countries, other difficulties arise. Transportation of produce through long distances in ill-paved roads adds to the costs. Local machining depends on power supply, which is not always available in remote regions. Considering the phasing suggested in Wikihouse.cc, the fourth one - Digital Decentralised seems just so far from reality when developing countries are considered.

Figure 9
1/3 Scale Prototype complete assembly.

Future development
The team is beginning the production and construction of the first 1/1 prototype. Final results are expected for 2019, October.

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Prototyping a Facade Component

Mixed technologies applied to fabrication

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During the last decade, mass customization in developing countries has been rising. The combination of conventional methods and materials with computer numeric control technologies offers a possibility of merging established craftsmanship to the production of personalized components with mass production efficiency. This article aims to present the development of a facade component prototype as a means to prospect possibilities for mixing parametric design and digital fabrication to casting, especially in developing countries like Brazil. This is an applied research with an exploratory and constructive approach, which was a result of a graduate class structured on a research by design basis. The conceptual development and prototyping of the artifact followed iterative cycles, considering its performance, fabrication methods and feasibility. The selection of materials that are commonly used in Brazilian architecture, like concrete, facilitates the component adoption as as a facade solution. The main conclusion emphasizes the need of involvement between academia and industry for the development of innovative products and processes, and highlights different levels of mass customization to include a range of manufacturing agents, from major industries to local craftspeople.

Keywords: *digital fabrication, mass customization, prototyping, facade component*

INTRODUCTION

The middle of the XX Century was marked by the Third Industrial Revolution (Rifkin, 2011), with the automation of production, which allowed the introduction of the concept of mass customization (Bunnell, 2004). Pine II (1993) defines mass customization as the possibility of increasing variety in goods and services without a corresponding rise in costs. Lampel and Mintzberg (1996) identify that modifications according to customers' needs can happen in four different moments: design, fabrication, assembly and distribution. In the field of architecture, the association between parametric design and digital fabrication is the key for developing mass-customized solutions (Kolarevic, 2005; Kolarevic and Duarte, 2018), besides from allowing the exploration of geometries that, previously, were difficult to design and produce (Kolarevic, 2005).

While in some areas and countries this concept was rapidly introduced, in others it was a lengthier process. Among several reasons, the low availability of technology and its high cost, when compared to traditional methods, are highlighted. However, some authors identify that computer numeric control (CNC) technologies have already been available in the construction industry for more than a decade. In Brazil, Silva et al. (2009) have mapped several industries in the Federal District which own CNC equipment. Similarly, Barbosa Neto (2013) found out in the technological park of Campinas that industries do not make the most of the machinery available, utilizing high-tech equipment to perform simple tasks. Thus, this mismatch between digital fabrication and the construction industry seems to be more related to cultural characteristics, such as a lack of dialogue between architects and manufacturers, both in academia and in practice (Silva et al., 2009).

In the last few decades, the enhancement in the conception and production processes provided by digital technologies resulted in a change on the traditional sequence of the architectural design process. As discussed by Rivka and Robert Oxman (2010), shared digital representations, combined with rapid prototyping and digital fabrication, shifted the spotlight back to tectonics and allowed materiality and structure to be in the genesis of design. Those authors called this movement New Structuralism, which relates to the focus on material as a primary design concern, followed by structure and lastly, by form. This is exemplified by the brick facades developed by the Gramazio Kohler team, which combine the digitally informed process of prefabrication with a sustainable on-site construction, through a system of masonry in a robot-based manufacturing process (Gramazio and Kohler, 2014).

In the context of developing countries, this balance between digital and analog, mechanical and artisanal processes is even more relevant. Since some digital technologies have not yet arrived in most construction sites, it is necessary to make the most of materials and technologies that are already known with low cost digital technologies, in order to apply the New Structuralism principles. According to Yuan (2012), digital fabrication technologies provide a different kind of transition in developing countries, with the rise of CNC craftsmanship, where artisans can make a smoother adjustment from low to high-tech approaches since, unlike other countries, industrialization has not completely reached the construction sites. They also redefine the dialogue between architects and construction workers, as drawings start to be no longer the main communication document (Yuan, 2012).

In Brazil, despite those barriers, there have been several attempts to explore complex geometries. However, in many cases, the technology or specialized manpower required are not available. This has been bypassed by mixing high technology (or concepts) with the development of an assembly process that could be automated or manual. One example is CoBLOgó, a brick facade developed by SubDV that worked as a second skin to an office building in São Paulo. The project used high technology during its development (parametric modelling and environmental simulation) and traditional manpower for its assembly, by using a non-specialized workforce and digitally-cut templates (Celani, 2016; Sperling and Herrera, 2015).

In Latin America, many other examples were highlighted in both editions of the Homo Faber exhibition, in 2015 and 2018, which presented works produced in university and professional scenarios with the use of parametric design and digital fabrication (Scheeren, Herrera and Sperling, 2018; Sperling and Herrera, 2015). The last edition, in 2018, also brought a more in-depth perspective on the connections between this process and local culture. The Colombian company Frontis3D was featured in both exhibitions with facade components for environmental performance. The proposal for Square 85, for instance, combined environmental simulation and parametric design, through an iterative process, to generate custom perforations in metal sheets. Panels were positioned in front of existing windows to enable natural lighting and ventilation without compromising the view to the outside (Scheeren, Herrera and Sperling, 2018).

Another example is the tile fabrication developed by students in the fabrication laboratory at Universidad Piloto de Colombia, which combined both digital fabrication and artisanal techniques. Parametric modeling and 3D printing were used to design and fabricate a first mold. Artisanal techniques were then applied to create a clay negative mold, where plaster was casted to generate the final tile (Scheeren, Herrera and Sperling, 2018). This approach allowed them produce several tiles with a complex geometry in a reasonable time at low cost.

The present research is inserted in this scenario as an outcome of a graduate class called "Design for Innovation," led by Dr. Gabriela Celani at the University of Campinas (Unicamp), in Brazil. The proposed brief was to rethink the concept of facade as an opaque element with window openings, through the design of a different kind of facade that responded to two or more environmental issues with the use of innovative techniques. The facade should be designed for a building in Campinas, even though the solution could later be adapted for different locations.

The research began with the problem of controlling light, wind and sound with a facade element. Currently, a window is used to control these elements, however, if a window is opened to provide air circulation, there is no external noise control. This problem was reframed with the question: does the passage of light and wind need to be provided by the same element? If these two functions were dissociated, could an element be developed to control wind and sound, in order to simultaneously provide air flow and improve acoustic comfort?

This article will focus specifically on the development and the production of physical prototypes for a facade element, considering the technological limitations and the non-specialized workforce available in the Brazilian scenario. Although environmental performance was an important design concern, it will not be explored in this paper. Therefore, the goal of this article is to raise possibilities regarding the use of mixed technologies in the mass customization of facade components, through the exploration of this scenario in the literature review and the development of a prototype. This facade element was conceived in this context, alternating between an automated and digital production mode, and traditional construction techniques combined with performance-based design (Oxman, 2008) that considered ventilation, acoustic comfort and other factors. Different production methods were explored in order to execute complex geometries within a conventional medium, while maintaining the desired precision and low cost.

METHODS

This research takes an exploratory and constructive approach. The development of the facade component considered that the systematization of a design process can lead to innovative knowledge, going beyond the artifact itself (Simon, 1996). The research question guided the development of the component, which was achieved through practical experiments, integrating the design process with new methods of production (Hauberg, 2011).

The design framework started from reconsidering the hierarchy of layers in a facade. Instead of ordering distinct layers to solve issues of light, air, moisture, view and moist ((Emmitt, Olie and Schmid, 2004)), elements were combined into a single layer, with a focus on light, air, and the added layer of sound. This conception of a merged layer guided all modelling and fabrication processes.

The component was modeled using Rhinoceros 5.0 and Grasshopper, and the plugins RhinoCFD and Diva were used for environmental analysis. The prototypes were digitally fabricated using a Felix FDM 3D printer, a Vitor Sciola 3-axis CNC router and a vacuum forming machine.

As for the materials, styrofoam was used for milling, polylactic acid (PLA) for 3D printing, polypropylene for vacuum forming and concrete for casting. In order to explore the reduction of costs and the reuse of materials, in addition to the traditional polypropylene sheet, disposable plastic plates and plastic folders were tested for vacuum forming.

Once the vacuum formed design was produced, it was used as a negative mold and embedded into the concrete component prototype.

DESIGN AND FABRICATION OF THE FACADE COMPONENT

The geometry of the facade element was developed through the interaction between its performance and the fabrication tests developed. Due to the complexity of the shape, the first step in the development and production of prototypes was to select the manufacturing process. Initially, three major methods were considered, according to references from the literature: stacked 2D cut layers [1], 2.5D milling (Iwamoto, 2009) and casting (Hensel; Menges; Weinstock, 2010; Dunn, 2012).

The stacked layers would simplify the complex geometry, affecting its performance, and also require additional effort during its assembly, due to the amount of layers. Considering the complexity of the geometry, 2.5D milling would not be able to accurately carve the desired shapes, requiring more advanced machinery, such as a 5-axis robotic arm. In both options, the geometry would be carved out from the material, resulting in the empty space desired, however, in the casting approach, a negative mold from the cavity would be created, placed and then the material would be poured around it. This allowed more flexibility in the element's geometry, adapting the process to the machinery available at the lab. Another advantage of the casting method is its proximity with construction methods currently used in Brazil.

The initial model consisted of a simple geometry (Figure 1), which was easily halved and each half could be carved in styrofoam using a 3-axis CNC router. The carved model was used as a negative mold during the concrete casting. Initially, chemical dissolution was considered for removing the material from the casting, however previous tests had taken too long for the material to dissolve and a large quantity was consumed, therefore the negative mold was removed manually. Both scenarios required significant manual work to remove the styrofoam mold, leading to a reevaluation of the method used

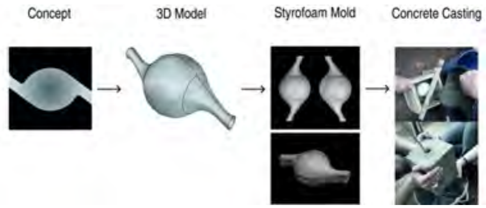

Figure 1
First prototype.
Source: Authors

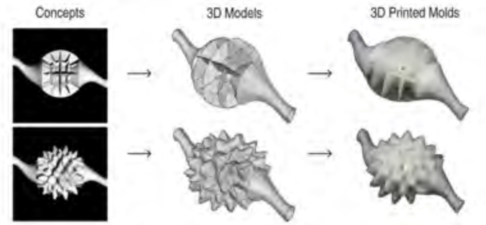

Figure 2
Second and third prototypes. Source: Authors.

The second and third models (Figure 2) underwent modifications based on sound performance, presenting more complex shapes that couldn't be fabricated by the CNC router available (2.5D milling). Potentially, those shapes could be milled on a 4-axis CNC router or 3D printed, but would present the same problem of the first model: removing the material after the pour. Furthermore, the model would be single-use. In order to address these problems, the negative mold was used as a mold for polypropylene in vacuum forming. This created a positive mold which worked as a skin that for the concrete to be poured around. Tests regarding the same model in milled styrofoam showed that the material deformed during the vacuum forming process, only enabling the creation of one polypropylene object from each styrofoam mold. Although the 3D printing took longer than the milling, it allowed more geometric possibilities and the mold could be reused. The following models were then 3D printed to scale (1:4).

The first two polypropylene molds presented problems regarding their accuracy to the original design. Suction channels and flaps were added to improve the accuracy. As the models were to scale (1:4), it was possible to explore the use of different materials, thickness and temperatures during the vacuum forming. Disposable plates and plastic folders were tested as materials for the vacuum forming, which presented a good performance for scaled models.

The digital model was modified according to performance, maintainability and fabrication issues. It is important to note that the vacuum forming machine would not be able to accurately create a mold from the whole model, requiring it to be divided. The halves were 3D printed at 1:1 scale. Due to the increased scale, the disposable plates and plastic folder had to conform to a larger area, and during the vacuum forming process they presented tears or areas that were too fragile to be used. Therefore a standard sheet of polypropylene was selected. The two halves of the new vacuum formed mold were glued together and attached to a wooden box mold, into which regular concrete was poured. Concretes with a variety of aggregates underwent performance testing, analyzing factors such as thermal resistance and weight. Despite regular concrete having been selected for the final prototype, this process could be repeated with different materials that are best suited to local conditions. The plastic vacuum formed mold was incorporated to the final prototype and the 3D printed model could be reused to create other molds. The final prototype is shown in Figure 3

DISCUSSION

The technological evolution has led to major changes in the way buildings are designed and produced; however, due to limitations, it is necessary to embrace the technology and workforce available. For the development of the facade component described in this article, other technologies could be used, such as a 4-axis CNC router, 5-axis robotic milling, concrete 3D printing and many others, which were neither available in the lab nor common in Brazil, as well as different casting materials.

In the last few years, 3D printing technologies became more accessible, with the establishment of national brands, the availability of several DIY kits, and the emergence of makerspaces and fablabs open to the public. This movement reinforces the possibility of a gradual adoption of these technologies in civil construction. Additionally, in the component prototype, the main material used for the pouring was concrete, which is largely used in local construction. This approach seeked to make the most of cutting-edge technologies without neglecting conventional construction knowledge.

The combination of technologies was fundamental for the facade component development. Complex geometries provided by parametric modeling could only be turned into a physical object after a

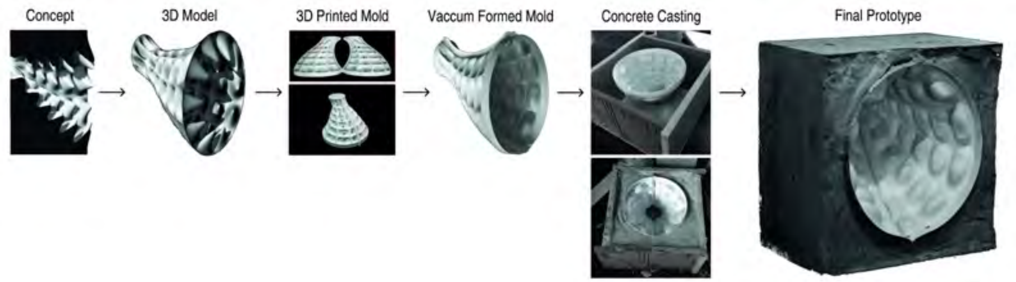

Figure 3
Final prototype.
Source: Authors.

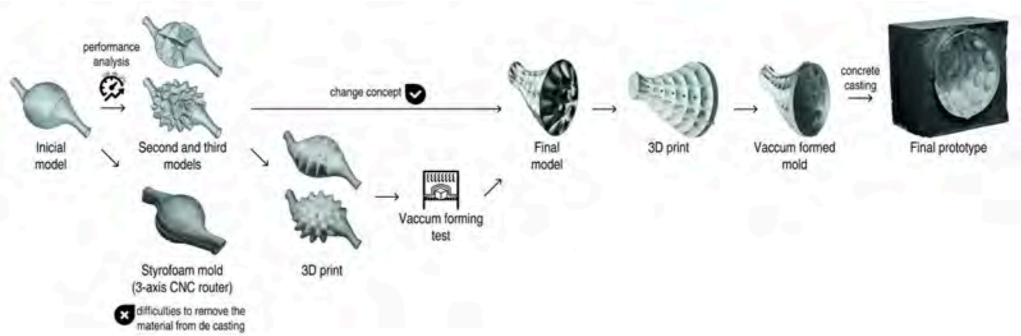

Figure 4
Summary of the iterative cycles in the prototype production. Source: Authors.

series of iterative experiments with materials and machinery. Form was a result of a performance-based design that took into account materiality and production processes, as shown in Figure 4.

Mass customization of the component could be achieved in several ways. The geometry of the component can vary in diameter, depth, number and distribution of recesses, according to the desired performance. Furthermore, the material to be poured into the molds can be chosen according to climate specifications.The prototyping of the component in an academic environment also raised a discussion about possible ways of creating a large-scale manufacturing product, with two main possibilities being identified (Figure 5). The first one is the manufacturing of individualized components, prefabricated off-site and assembled one-by-one in the construction site. Considering the cost drop of digital fabrication machines and the growth of distributed manufacturing, the components could also be produced in less centralized circumstances.

The second alternative is the fabrication of complete modular walls, similar to Gramazio Kohler's (2014) brick facades and the prefabricated modular units in Brazil. An example is the manufacturing of some building modules, in which the walls and floor are cast in concrete at the same time, with predefined ducts for electric and hydraulic installations. After that, the finishing processes are completed offsite, and the prefabricated pods are transported by truck to the construction site (Teribele, 2016). This second approach converges to the modular strategy for mass customization proposed by Kieran and Timberlake (2004). According to them, offsite fabrication combined to the subdivision of a problem into smaller parts makes it easier for each part to be customized through an integrated process, which also leads to better work conditions.

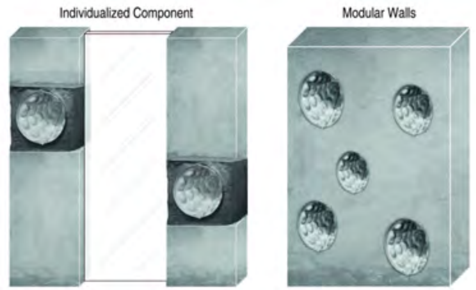

Figure 5
Two possibilities of mass customizing the facade component with mixed technologies. Source: Authors.

Even though the model is parametric, which allows its customization through changing determined variables, it would not be feasible to 3D print hundreds of molds for a singular wall or building. However, producing at a small series scale could allow a determined variety of models (such as ten different iterations) for creating all the components to be distributed along the wall or building. In the simplest approach, one single 3D printed model could be optimized for a specific situation or site and then used for generating all the components for the whole wall.

CONCLUSIONS

To think about the mass customization of a facade component with the use of mixed technologies has some implications for the moments when user-driven modifications can happen, according to the chosen kind of production chain. As seen, customization can happen in the design, manufacturing, assembly and distribution of a product or service (Lampel and Mintzberg, 1996). The identified strategies imply different processes. For the production of an individualized component, customization could occur in the design and fabrication stages; however, as the components would be delivered similarly as isolated bricks, its assembly would happen in a more traditional way. Using strategies like the digitally-cut templates applied by SubDV (Celani, 2016; Sperling and Herrera, 2015) could improve this process. If the manufacturing of the individual components happens directly at the construction site, the range of customization is even more restricted. In this sense, although it is possible for the design of a component to be mass-customized for a given building or wall, its fabrication and assembly will be closer to an artisanal scenario than to a massified one.

The second approach presents the possibility of mass customization during the design, manufacturing and assembly phases. As the components will be embedded into complete walls with industrial precision, assembly takes advantage of a modular approach with a combination of efficiency and variety.

The product development process described above was carried out with a mix of high-tech and conventional construction methods and materials from Brazil, during a graduate course. On the other hand, this prototyping process could also be optimized with the introduction of new technologies that are not available on the Brazilian construction market. This scenario reinforces the assertion that, while in Europe and in the United States the introduction of new technologies in construction arises from the professional practice, in Brazil the innovation is emerging from schools of Architecture (Celani; Lenz, 2014).

Future work could encompass experiments with different molding materials, such as silicone, to allow its removal from the component. Tests with different materials that are more traditional in the Brazilian context, such as ceramics, and also more appropriate to warmer climates, would also be important to evaluate the component's feasibility for different weather conditions, in addition to playing a central role in a New Structuralist approach.

In summary, all the possibilities highlighted are not mutually exclusive; instead, they illustrate a range of opportunities for gradually incorporating mass customization of a facade component by taking advantage of the technology and workmanship available in a given situation. In that sense, partnerships between universities, architecture professionals, industries and craftspeople could foster this process through the establishment of integrated strategies.

ACKNOWLEDGEMENTS

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[1] http://www.iaacblog.com/programs/sound-absorber/

Option One-second Iteration

Analysis, evaluation and redesign of a rural housing prototype

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In 2005, the rural housing deficit in Colombia was 1,600,000 units, which is equivalent to 68.25% of the total households. This very high number shows the difficulties faced by public policies on rural housing. This deficit is partly due to logistical problems related to the supply of materials and complexity in construction processes. It is necessary to explore new alternatives to offer more and better homes at lower costs. The research project presented in this manuscript started in 2013 as an initiative to reduce the housing deficit. It proposed to build a rural housing prototype integrating digital manufacturing processes. The performance of part of the structural and enclosing system was evaluated during a first iteration process to include changes in a second iteration later. With the adjustments to the design process discussed here, the prototype is expected to be built and tested to measure its efficiency and functioning.

INTRODUCTION

Public policies on rural housing in Colombia face complex difficulties due to very high housing deficits. For example, in 2005, the rural housing deficit was equivalent to 1,600,000 units, (68.25% of the total number of households). The main reasons are linked to logistical problems related to the supply of materials and complexity in some construction processes (Simioni 2007). This highlights the need to explore new alternatives and technological possibilities to produce more and better rural housing at lower costs (Ottokar 1997).

The present research project, which started in 2013, aimed to build a rural housing prototype integrating digital manufacturing processes. This process comprises different stages and principles, which have been modified and refined through iterations. A first prototype was initially consolidated and built (Velandia 2015). Its monitoring, analysis and evaluation allowed further adjustments to improve efficiency and performance during a second iteration.

The structural and enclosure components of the prototype were designed and the mechanical system is in the process of definition and consolidation. The entire prototype is expected to be built in the near future to be lived in and tested by a family.

INTEGRATED DESIGN PROCESS

This work suggests an integrated design and production process, which goes beyond a single housing prototype by exploring the potential of digital manufacturing, exposed in previous literature (Barrow 2006). One of the main objectives of the process is to allow variations, from the definition and integration of dynamic parameters, which can be adjusted according to specific conditions, generating different options in the final result (Duarte 2001).

In this context, four design principles were used as the theoretical framework for the integrated design process of the rural housing prototype. These, among other aspects, allowed different actors to be involved in the definition of dynamic parameters (e.g. according to the conditions of each user, context and materiality) and manage the different stages of design, manufacture and assembly.

The four principles were:

1. Definition of a context, population or environment: These definitions should not be either too specific (as there are very few opportunities to replicate the methodology) or too general (as there is not a single answer that solves all the problems). This stage implies the recognition of possible local technologies and materials, climatic or geographical aspects.
2. Integration of the design, manufacturing and assembly stages: The CAD / CAM tools are fundamental at this stage. It is argued that the elements and prefabricated systems are the primary strategies, to guarantee quality, precision, control in the execution, stability and habitability of the house (Ulrich 2012).
3. Community inclusion and empowerment during the process: Tangible and intangible aspects must be recognised and linked to the integrated design process. This implies the analysis of relevant cultural, social, economic and traditional aspects, which could be integrated into the home. It also implies the identification of local materials and technologies that can be used. The community should be involved through training processes to understand and apply the technologies to be used in the construction and manufacture of the houses. This could improve their skills, abilities and knowledge and also improve the socio-economic conditions of the community.
4. Definition of a strategy and scope for user participation. It is aimed that the house users could be directly involved during its construction. Therefore, the user participation strategy must be as clear and as simple as possible. The final objective should be to guarantee the construction quality, despite the qualification of the available workforce.

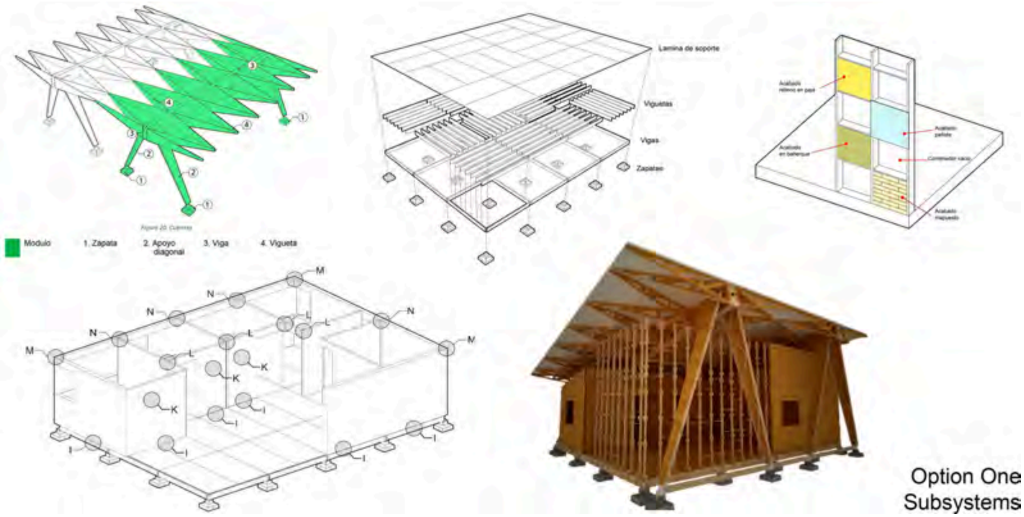


Figure 1
Option One.
Subsystems

OPTION ONE: THE FIRST ITERATION

A prototype of rural housing was proposed in past research by applying the four design principles mentioned above, divided into four subsystems: roof, base, enclosure and mechanical system (Rush 1986). Each system works independently allowing greater flexibility and the possibility of future adjustments and modifications, similarly to the user participation strategy (Velandia 2015). For the present project, it was decided to use timber (pine and OSB boards) as the primary material for the structural and enclosing system. All components were manufactured using a CNC router. The general system is complemented by steel joints to assemble the different elements and components.

The fundamental characteristics of each subsystem were:

Roofing:

- It consisted of two self-supporting modules. A total of 8 supports were used..
- 9m long main beams and 2.6m long joists.
- A prefabricated, reinforced-concrete slab-foundation.
- Steel joints system for wood-wood and concrete-wood assemblies.
- Pine , OSB boards and steel were the predominant materials.

Enclosure:

- It comprises a sandwich type system, with a central core onto which different finishes can be attached. The core consists of a structure and enclosure in pine and OSB boards. The final coating is a composite enclosure, which is fabricated using local materials.
- A mechanical joint between the enclosure system and the base is proposed, to allow and facilitate the elements´ change or modification (spatial flexibility).
- It was decided to use connectors different to nails or screws, as these may be unavailable in remote areas.
- The primary materials were pine and OSB boards

Base:

- The base was structurally separated from the roof to increase the degree of spatial flexibility. The total initial base area was 72 m2.
- The base was proposed as a modular system, which could be extended in the future by the addition of modules.
- 2.40 m long beams and joists to match the OSB board size.
- Prefabricated, reinforced-concrete slab-foundation.
- Steel joints system for wood-wood and concrete-wood assemblies.

Figure 2
Option One.
Second iteration.
Construction
process

Figure 3
Students group

- Mechanical joints to link to the enclosure system.

Mechanical system:

- Elements and components designed to be attached after the construction of the base and enclosure.
- Modular elements that allow updates and modifications.

FIRST ITERATION: ANALYSIS AND EVALUATION

The first approach to the manufacture and assembly of the prototype showed different essential aspects for the re-evaluating and improvement during a second iteration. One of the conditions to be verified and evaluated was that a group of 4 to 6 people could assemble the prototype without the need for specialised machinery or tools.

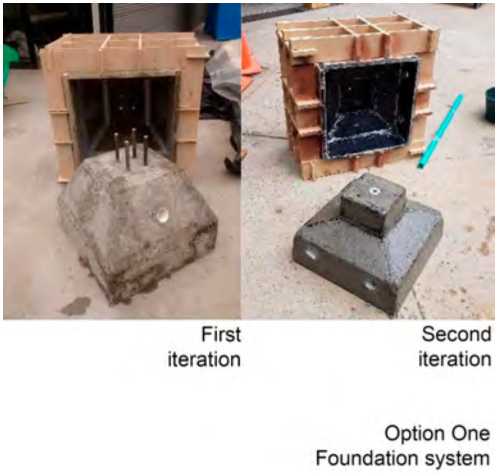
The analysis and learnings from the first approach could be summarised as follows:

- The foundation used was very heavy, which made it challenging to move elements from one site to another. It was necessary to decrease the final weight of the foundation components and to think about a transportation strategy.
- Many of the steel joints significantly increased the weight of the components, making them difficult to handle, transport and assemble. An interdisciplinary effort was necessary to redesign and optimise the joint system of the entire prototype.
- Some joints presented precision and constructive stability problems, when added after the prefabrication process (e.g. perforations or screw fixing). It was necessary to define the location of additional elements more accurately to avoid problems of precision and technical coordination.
- The 9m long beams for the roof were challenging to assemble. The main beam was very heavy. The beam supports located at 4.5 m above the floor were also complex to assemble due to excessive weight. It was necessary to modify the dimensions of the larger ele-

Figure 4
Enclosure system

- ments to reduce their weight and make them easier to manipulate.
- Eliminating the use of screws was an initial goal. However, it was necessary to use them in different elements and components of the prototype. One of the future objectives is to continue developing fastening systems other than screws or nails.

Figure 5
Option one.
Foundation system.



OPTION ONE: SECOND ITERATION

The second iteration of the housing prototype began by making adjustments within the integrated design process, based on the analysis and learning from the first iteration.

The adjustments made were:

- In order to reduce the length and weight of the elements, the total area of the base was reduced from 72 m2 to 48 m2.
- The roof beams were reduced from 9 m to 6 m in length.
- The height of the beams´ supports for the roof was reduced by 1.5 m.
- The foundation was redesigned to reduce weight, integrate elements to facilitate the transport of the main components and an additional joint to assemble the foundation with both the roof and the base systems.
- The heavier joints were redesigned to reduce weight and facilitate their handling and assembly.
- The use of screws as a joining system was reduced to the minimum.

Once the prototype was adjusted, the new elements were fabricated, and the assembly and assembly process was defined. Due to resources and time restrictions, it was decided to build only one of the roof-system modules, and half of the base system, as well as the assembling elements for one of the enclosure-system modules.

The construction of the prototype was included as part of an academic exercise at the University in the summer of 2018. A team of approximately ten people (between teachers and students) with no previous experience or training in construction was involved in this exercise.

Figure 6
Steel joints system

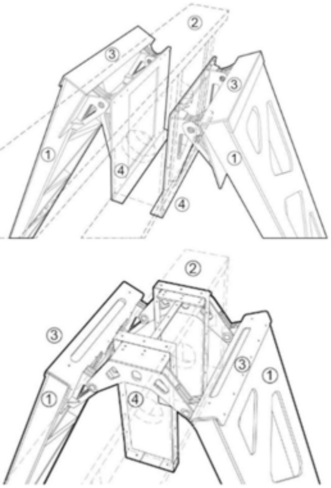


Figure 7
Option One.
Structural joint.

SECOND ITERATION: ANALYSIS AND EVALUATION

The construction of the roof, base and enclosure was carried out successfully. The total effective construction time was 10 hours (having all the prefabricated elements ready). The fabrication and assembly of the second iteration of the housing prototype allowed the identification of some positive aspects and other aspects to be reviewed.

Positive aspects:

- The process of prefabrication of elements was successful. It was not necessary to modify or elaborate on new elements. In general, the construction system was efficient.
- The manipulation of the individual elements and components did not present significant difficulties. This showed that the adjustments in terms of dimensions and weight of the elements were appropriate.
- The performance of the steel joints was good, except for some particular cases, where they were still very heavy or difficult to assemble.
- The students (unskilled labour) experienced a fast learning curve regarding the manufacturing and assembly process. This evidenced the importance of including this aspect from the early stages of the design.

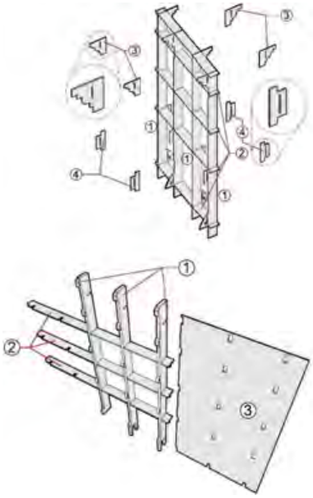


Figure 8
Option One.
Enclosure system.

Figure 9
Final Result

- The modules of the enclosure system performed well in terms of their manufacturing and connection to the base. No screws or nails were used.
- The articulated joints that linked the roof support to the foundation displayed excellent performance, facilitating the manipulation and assembly of the structural modules.

Aspects to review:

- The modifications made allowed to reduce the weight of some elements and components considerably. However, the handling of some of them, especially the roofing components, presented difficulties. This implies the need to rethink the elements of the structure and the construction systems in order to make them lighter and more comfortable to manipulate. In this area, new and more efficient alternatives must be sought for the beams and supports of the roof modules.
- Although in this second iteration, the weight of the steel joints was reduced, it is important to continue developing lighter and more efficient joints, to avoid the use of screws as much as possible.

Pending issues:

- It is expected to build the whole prototype in the near future.
- It is expected to define a specific context for the location of the prototype, in order to integrate local materials, particularly for the enclosure system.
- It is necessary to integrate the development and production of the mechanical system into the prototype.

DISCUSSION

It has been demonstrated so far that an integrated digital manufacturing process applied to rural housing is viable, combining technical-constructive variables, context variables, and user variables.

The second iteration - as part of a continuous process of evaluation and learning - also showed a wide margin of optimisation and improvement in performance, which the housing prototype can have.

The time used for the prototype´s assembly during the second iteration (10 hours), exceeded the initial expectations, validating the decisions regarding the design of elements and joints.

Additionally, the process showed that unskilled labour could be involved, without affecting the final quality of the product.

All of the above suggests that a rural housing prototype with the characteristics shown here is viable and applicable to the Colombian context, with the currently available technology.

However, further development is necessary regarding technical aspects (e.g. the mechanical system) and financial aspects to allow an integral evaluation of the economic viability of this type of technology for a rural environment. A fundamental step for this is to have the prototype built in its entirety, which is expected to happen at the end of 2019. This will help to evaluate the integrated digital manufacturing process and the overall performance of the construction.

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Design Method Aided by MABS and Cloud Computing

Framework integrating: construction techniques, materials, and fabrication

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This paper presents a novel method based in Multi-Agent Based Simulation (MABS), Cloud Computing, and the combination of big data analytics and IoT. The method performs in two layers: it assists designers with information coming from previews of projects and surroundings, and, it automates some procedures according to parameters and interactions between agents. The first part of this paper briefly describes the state of the art and challenges of the real estate market. The second chapter highlight gaps and future challenges in design practice, and in the third chapter, it introduces the method. To conclude, in the last part, this concept is analyzed through a pilot project under development in our institution.

Keywords: *Computational design, Multi-Agent-Based system, Robotic fabrication, Cyber-Physical Systems, Big Data, Internet of Things*

INTRODUCTION

Industry 4.0 deals with a variety of emerging technologies, with a significant impact in information management and great potential to increase productivity in the manufacturing process. With the use of advanced computing, big data analysis, robotics, and digital manufacturing new horizons are envisioned, in which better and innovative processes have made the industry more efficient and able to meet demand with more personalized and sustainable products and services (Hemmerling, Cocchiarella 2017, p.40). From the combination of these technologies, among other things, Cyber-Physical Systems (CPS) and the Internet of Things (IoT) have an essential role in the efficient and digital fabrication of buildings in the near future.

Concerning building efficiency, although not largely implemented, IoT is already a reality. Building automation, management systems, security, HVAC and lighting performance are some of the possible applications that, combined with CPS or digital twin can provide a platform to interpret data in real time and anticipate actions when necessary. However, the information gathered in a digital twin is not only an asset to optimize the project in itself and monitor the life cycle of a building. The information embedded is a valuable tool to analyze design decisions and fabrication processes, constituting a key element to assist and drive architects and engineers in a future open network (IoT + big data analytics).

A Multi-Agent Based System (MABS) can be described as the interaction between individual agents to reproduce phenomena or system, simulating "n" possible outcomes. Each agent receives a specific task and assumes relevant attributes and constraints. Through these interactions, between agent to agent and agent to environment, the model pursues a global equilibrium. MABS often adopt a bottom-up schema where agents compete and negotiate considering local rules in a complex scenario (Gilbert 2008).

1. PROBLEM

By 2050, around 70% percent of humankind will live in urban areas [3]. It means that, in the next decades, the demand for houses in urban centers will only grow. Analyzing profitability indicators for the construction industry, noticed that, in the 90s, the sector reached its peak and, from there on, it staggered or even declined (Rifkin 2018).

Looking into the german context, and comparing the disbalance between demand, license to build and completed constructions annually [7], the lack of efficiency in the construction sector becomes even more evident. Nevertheless, the waste of human resources is not the only factor. The construction sector is also one of the most polluting on earth [4]. Traditional techniques can be characterized by:

Project phase:.

- Long time in the design phase, since every project is designed as an unique product.
- During the process, any change in the budget or/and the concept causes delays, rework, and additional costs.

Construction phase:.

- Waste of resources by manufacturing on site (uncontrolled environment).
- Constant rework caused by unforeseen issues (delay).
- Hostile work environment (many accidents at work).
- Long periods of construction on site (higher labor costs).

Additionally, the regulations regarding work protection, as well as environmental protection, are getting more restricted every day. Consequently, the construction sector urgently needs to find new solutions to reduce its carbon footprint and increase its productivity.

To overcome these issues, we have been witnessing the progressive implementation of Building Information Modeling (BIM) in the industry. The American Committee of the National Information Model Standard Project defines BIM as "a digital representation of physical and functional characteristics of a facility... and a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition" [5]. And the U.S. Government General Services Administration defines BIM as "the development and use of a multi-faceted computer software data model to not only document a building design, but to simulate the construction and operation of a new capital facility or a recapitalized (modernized) facility" [6].

Although this growing implementation corresponds already to a significant advance to the design practice, the overall mentality throughout the industry persists the same. Object by object, part by part, designers create all information necessary to each project; that is, each project establishes a closed cycle in itself and the data extracted from them is used exclusively within its ecosystem.

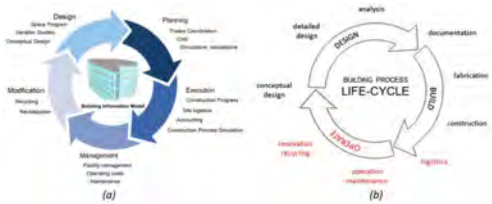

Figure 1
BIM Life-Cycle (a) (Borrmann, König, Koch and Beetz 2015, p.4) (b) (Hemmerling, Cocchiarella 2017, p.40)

Comparing the model above with the organizational model suggested by the 4th industrial revolution (see figures 2b and 2c) it is clear that we are still using the previous model of centralizing characteristics (see figure 2a), where the learning process acquired in each project is transferred to the next empirically, and not shared with the network.

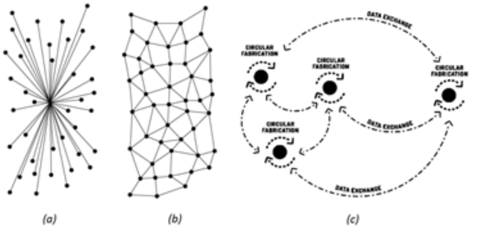

Figure 2
Centralization vs Distributed [1] [2]

2. HYPOTHESIS

At this point, we can conclude that it is not only necessary to have better software and better machines. The benefit comes when the model is capable of pulling and filtering information in a continuous optimization process, where the adaption occurs when agents learn from each other or change strategies as they gain experience.

Rather than an additive process, the interaction between agents should follow conditional and non-linear methods, the parts and the interaction between them must be studied simultaneously. According to Holland (2000, apud Baharlou and Menges 2013), “One procedural approach, is to organize such complexity through a computational framework that incorporates its elements, rules, and interactions... The proper generative computational framework includes both mechanisms to generate possibilities and constraints to limit the range of possibilities”.

Therefore, this new model implies a questioning of traditional design methods. To open the possibilities for “n” design solutions, performance and shape must be intrinsically connected, and thus, domains and parameters should precede form.

It is also essential to acknowledge the need for a profound change in the concept of ownership embedded in each project. As mentioned earlier, the foundations of the digital revolution are anchored in the way it manages and cross-references information. Moreover, the exponential improvements to gathering and filter information, aligned with new production techniques, allows the implementation of mass customization.

Applying these concepts to the construction sector, it is necessary to integrate the whole industry in a lateral network between architects, engineers, city planners, construction companies, and city governors. Thus, from a shared database, it will be possible to improve efficiency in the design and construction processes exponentially, constantly targeting the needs of society as well as optimizing marginal costs and waste of resources. In other words, to consolidate this framework, new communication channels between the smart Building reports (massive IoT implementation category), industry, city regulations, and society, are needed.

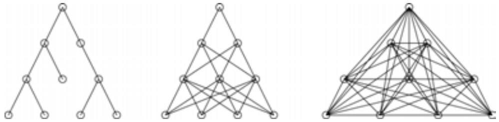

Figure 3
Cross-references information between parts and whole

3. METHODOLOGY

3.1. Concept

Based in highly constrained construction techniques, materials, and fabrication, a methodology of parametric design arose from current research in the constructionLab at TH-OWL. A framework to build models that integrate: design; structural performance; fabrication files, and construction drawings.

The method is based in Multi-Agent Based Simulation (MABS), Cloud Computing, and the combination of big data analytics and IoT. According to Drogoul, Vanbergue, and Meurisse (2002), in MABS systems, the design process relies on the different roles involved (in our case: Architects, Engineers, and Computer Scientists), and its versatility supports the simulation of complex systems. Cloud computing, in turn, delivers the necessary on-demand computing resources to simulate the models in real-time and “by defining sets of higher level functions (e.g., an Application Programming Interface (API)) that provide interfaces to several expert-level BPS software..." (Nembrini, Samberger and Labelle 2014), it is possible to extend the framework capabilities.

Also, hosted in a web application, the system allows not only its extension but also the simultaneous work of several models, and the straight communication with a database, scalable and integrated, provides practical information in all design stages.

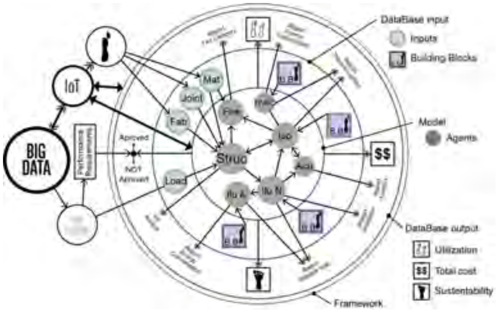

Figure 4
The framework architecture

3.2. Strategy

Parametric design, in theory, can compute the model of an entire building within a cell, originating families. By varying the values (parameters) that influence the model, it creates a unique project (Beesley, Williamson and Woodbury 2006). With this strategy, the framework "presents the problem and solution of each pattern in such a way that it is possible to judge and modify it, without losing the essence that is central to it." (Alexander 1977)

As a result, the adoption of technology in the design process has surpassed literal descriptive formalist approaches, evolving into a bottom-up method that integrates with versatile analysis tools for structure, thermodynamics, light, and acoustics, and evaluates the behavior of the system in interaction with the simulated environment (Menges 2008, p.196).

Furthermore, using "programming language, instead of drawing, it also matches the nature of the nonlinear design process made of refinements where each step compromises the project as a whole" (Oxman 2006, apud Labelle, Nembrini, Huang 2010). From this local and global intercommunication, two hierarchical layers work in a feedback loop:

The top layer provides a local domain of solutions for each agent, assisting designers to make informed choices. "At this layer, the aim is not necessary to get the best-fitted solution, but to do a probe in the surroundings of the bench-marked ones to explore qualities that when put together would then suggest architectural relations that needed to be best evaluated from a designer perspective" (Mena 2018).

And the bottom layer automates agents, highly dependent on performance behaviors. According to its data structure (internal mechanisms and constraints), and from the first design manipulation, these agents interact between each other, targeting an equilibrium in a global domain and consequently, narrow down their initial local domain.

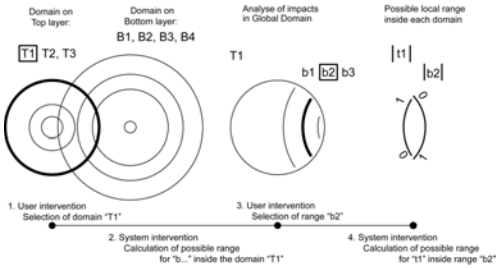

Figure 5
Graphical representation of the simulation between Top and Bottom Layers (Agents "T" and "B")

As more frameworks are developed in the network, the range of typologies and construction systems available to designers increases. Nevertheless, protocols are needed and should cover three main points:

1. Information security - although it works within an open network, the information generated must be provided anonymously. Blockchain technology suggests the use of a decentralized database that combined with highly secure cryptography, becomes - in theory -, one of the safest solutions (Mougayar 2016).
2. Standardization of metric units of measurement (physical and temporal), providing reli-

able and comparable indicators.

3. Standardization of modeling technology. In this regard, IFC proves to be the most appropriate tool to be used [5].

3.3. Design Method:

First, it is crucial to formulate the problem (objective functions), specifying intentions and boundary conditions. Drogoul, Vanbergue, and Meurisse (2002) define it as the Target Model, and call the experts in this phase as "Thematicians". In this phase, the characteristics to be taken into consideration are: Typology, construction technique, fabrication methods, materials, local resources, and even cultural aspects.

Once having all agents denominated, it is necessary to turn from macro towards micro decisions elucidating individual constraints (local domain) and relations between building blocks (global domain). According to Menges (2008, p.196), "the underlying logic of computation strongly suggests such an alternative, in which the geometric rigor and simulation capability of computational modeling can be deployed to integrate manufacturing constraints, assembly logic, and material characteristics in the definition of material and construction systems."

Finally, having the Domain Model as a guideline, the computational modeling of the agents begins. Starting from free-hand sketches, "designers write shape-describing code, abstractly creating and modifying objects through geometrical transformations"(Nembrini 2014). Here, to amplify the perception of system behavior, it is prudent to use not only parametric tools and 3d visualization, but also physical prototypes.

The aim goal at this phase is to translate the Domain Model in a Design Model that consists of a parametric model to be eventually implemented or optimized by a computer scientist (See figure 9).

As each agent will be responsible for different tasks in a complex and interdependent system such as the components of a building, the optimization process (minimization/maximization) becomes difficult or even impossible (Cagan, Grossmann and Hooker 1997). Therefore, defining the hierarchy and the optimization strategy implemented in the negotiation between agents should also consider feasible region solutions.

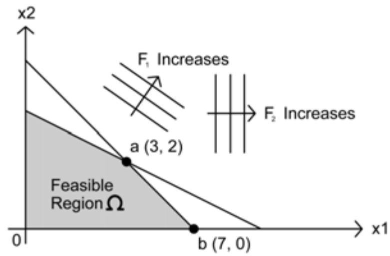

Figure 6
Multiobjective Optimization

4. CASE STUDY

4.1. Interface

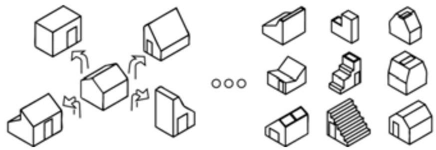

Figure 7
Interface: Hypothetical array of solutions

Although not fully implemented, the modeling interface will be initialized in the shape of a "primitive house"; then, using drag and drop commands, the designer can manipulate the envelope as he or she wishes. At this stage, no internal divisions and intermediary supports are possible, which limits the total size of the house. Additionally, the opening's building blocks (doors and windows) are fixed, requesting (like other agents) further development. Regarding the cladding, as a variety of wall assemblies are under investigation, the system will become resilient for different climates. Insulation, rainscreens, heating systems, and shading devices could all be incorporated into the system and regulated through the thermodynamics, light, and acoustics agents.

The diagram below highlights the agents integrated into the current study, so far. Next, we disclose its application and results.

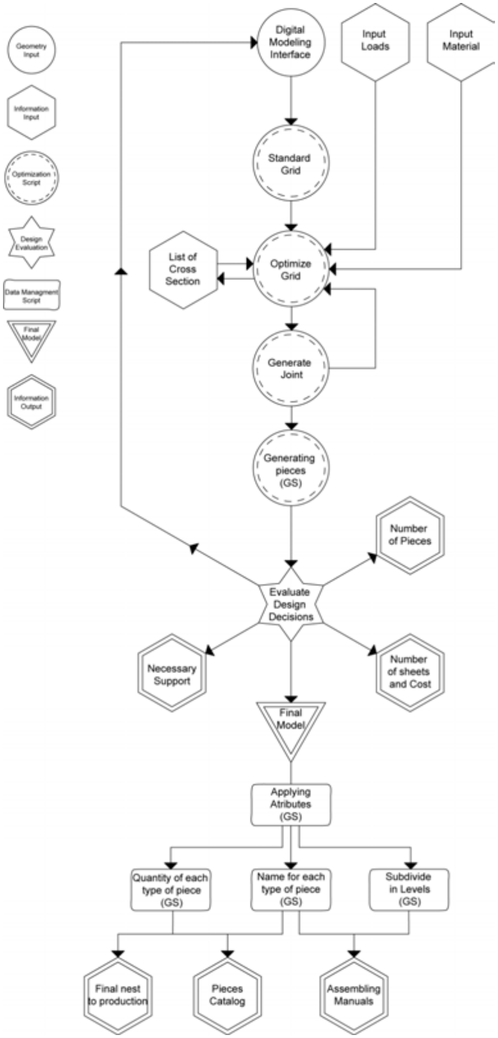

Figure 8
Diagram of structural agent procedures

4.2. Target Model

Considering the local tradition in wood construction, the growth of human flow and the lack of affordable dwellings in Germany, the study case presented in this paper targets tiny houses as typology. Next, taking into account that the majority of CNCs available in the market have only three axes, we decide to restrict the design solutions by using only manufacturing strategies feasible for this type of machine. Following the same principle, wood panels were adopted as a structural material. Besides being renewable and recyclable, they are easily found throughout the territory, which allows the manufacturing of the pieces near the construction area, promoting the local market and reducing transportation costs.

Figure 9
Big data analytics to assist design decisions

Finally, the research group defines that the assembly process should occur without the need for any machines or tools, and the solution should contemplate the possibility to assemble and disassemble the house several times.

4.3. Domain Model

At this level, examining the building's fundamental components, the central issues which underlie the study became, clear, and from the essential element responsible for connecting the parts (the joint), the cardinal rules that drive the structural generative system were formulated.

By limiting horizontal and vertical orientations, complex angular connections and extra fasteners are eliminated. Despite having no diagonal members, the vertical parts are offset in each layer, providing lateral bracing that resists shear forces.

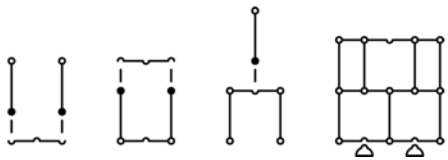

Figure 10
Assembly steps: cardinal rules

Figure 11
From the fabrication to the assembly

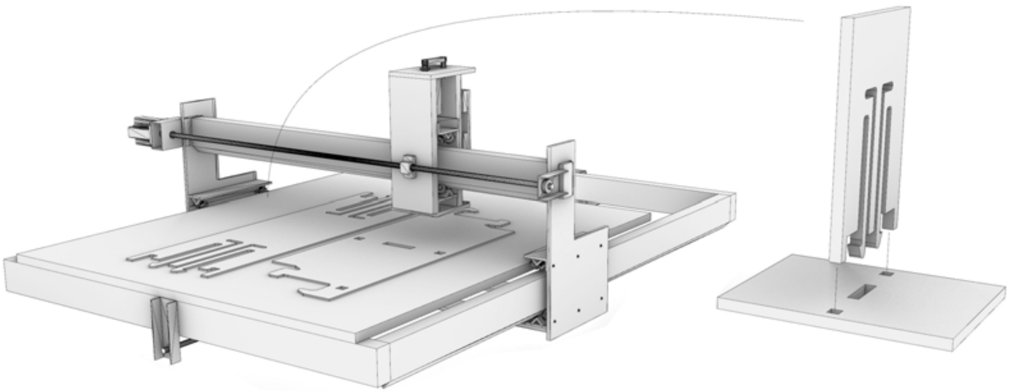

Figure 12
Main joint, secondary connection and transition between planes

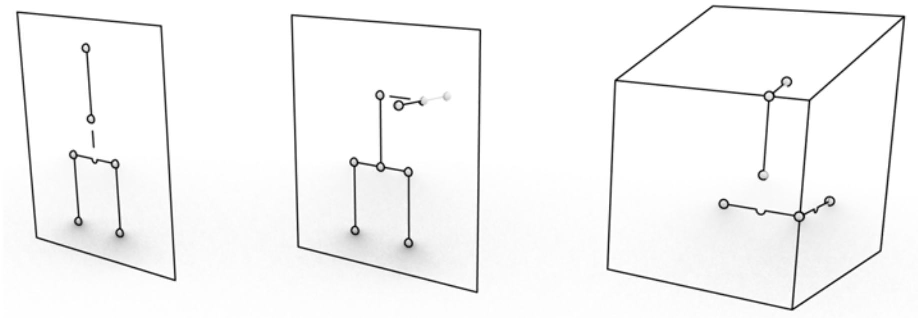

Figure 13
Photographic record of the assembly.

To facilitate handling the parts during the construction, the length of elements is limited. Vertical elements vary from 0.5 to 1.5 meters, and horizontal members can grow up to 2.0 meters. As a result, the loads acting on the structure are transferred through a series of small-scale framing layers.

The Joint:. The idea of the cutting operations was to perform every cut in the XY plane, limiting the milling to 90° degrees and allowing engravements only in the surface of the plates. Horizontal beams receive pre-cut slots that locate the vertical members, eliminating the need for any guesswork or imprecise onsite measuring. Both ends of the vertical columns are milled with a clipping mechanism that slides into the horizontal member and locks securely into place.

4.5. Design Model

Assembly Procedure:. After the initial prototypes, we began the investigation of the assembly movements and sequences. To avoid collisions and make the transition between planes, a secondary connection was included. Unlike the main joint, where the assembly vector follows the plane, in the secondary connection the vector is perpendicular to it, so the chronological order of assembly must be respected. Furthermore, the elements that touch neighboring planes, whether vertical, horizontal or inclined, function as transitional elements between planes, incorporating 3-nodes instead of 2.

Optimization:. The finite elements that constitute the structure of each plane have an original subdivision of one by one meter. As geometric changes are made or load parameters are applied, the structural agent recalculates geometry dependent loads, deformation, and stress in each finite element and node. Next, an optimality criteria approach finds the solution. Using the pre-dimensioned clip, the agent can include or eliminate members, increasing or decreasing the spacing between vertical and horizontal parts to reduce the stress at the critical node until it matches with the joint's capacity.

Like the grid, the cross-section is initialized with standard dimensions, and in case of no solution during the finite element optimization method, the structural agents request the next cross-section in a sorted list (see figure 15a).

Considering that the agent seeks to maximize structural stiffness, the spacing between the parts can result in a very dense mesh, which would lead to an excessive amount of parts and waste of material. To prevent this situation, the agent responsible for the rationalization of manufacturing and the agent responsible for calculating the overall cost request a new simulation. Using the next cross-section in line the system calculates a distinct, more spaced grid, and the agents compare both solutions using a conditional operation as follows:

```
pseudo code

sortList_cS = [n1, n2, n3, n4, n*]
cS = sortList_cS[n1]
#calculating material volume
vol1_mat
vol2_mat
vol*_mat
...
while sortList_cS.index(cS) <= len(
 ↪ sortList_cS):
    if (vol1_mat > vol2_mat):
        vol1_mat = vol2_mat
        vol2_mat = vol*_mat

    elif (vol1_mat < vol2_mat):
        return vol1_mat
    else:
        print ("Consider changes in
         ↪ the design")
        return vol*_mat
```

Outcome:. After a successful simulation, the result is a collection of documents, including (see figure 15b):

1. Cyber-Physical System that, on the one hand, monitors the life cycle of the building, and, on the other, sends information to the framework agents.
2. CAD file containing all parts of the model properly labeled with their assembly names and locations.
3. G-CODE and nested file with such pieces organized through an algorithm that distributes the parts in clusters of useful dimensions for cutting.
4. Technical drawings, showing the construction procedures and chronological order of assembly.
5. Spreadsheets including a discrete list of parts; the specifications and amount of material; unitary and global costs.
6. Simulation reports coming from the analysis tools for structure, and later on, thermodynamics, light, and acoustics.

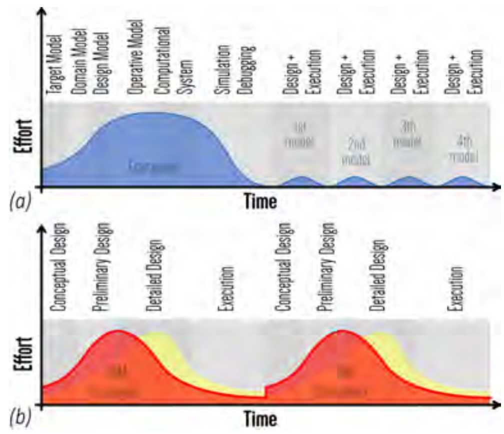

Figure 14
Function Effort / Time

5. CONCLUSIONS

This paper has presented a novel design method where the automation of production is embedded in optimization procedures and parametric design works with design assistance tools supported by data mining. The implications of this method are demonstrated through a case study. The analysis and tests prove consistency between virtual simulations, fabrication, and physical model. Also, it shows a rationalization of material resource and structural architecture.

Taking the agent responsible for the structure

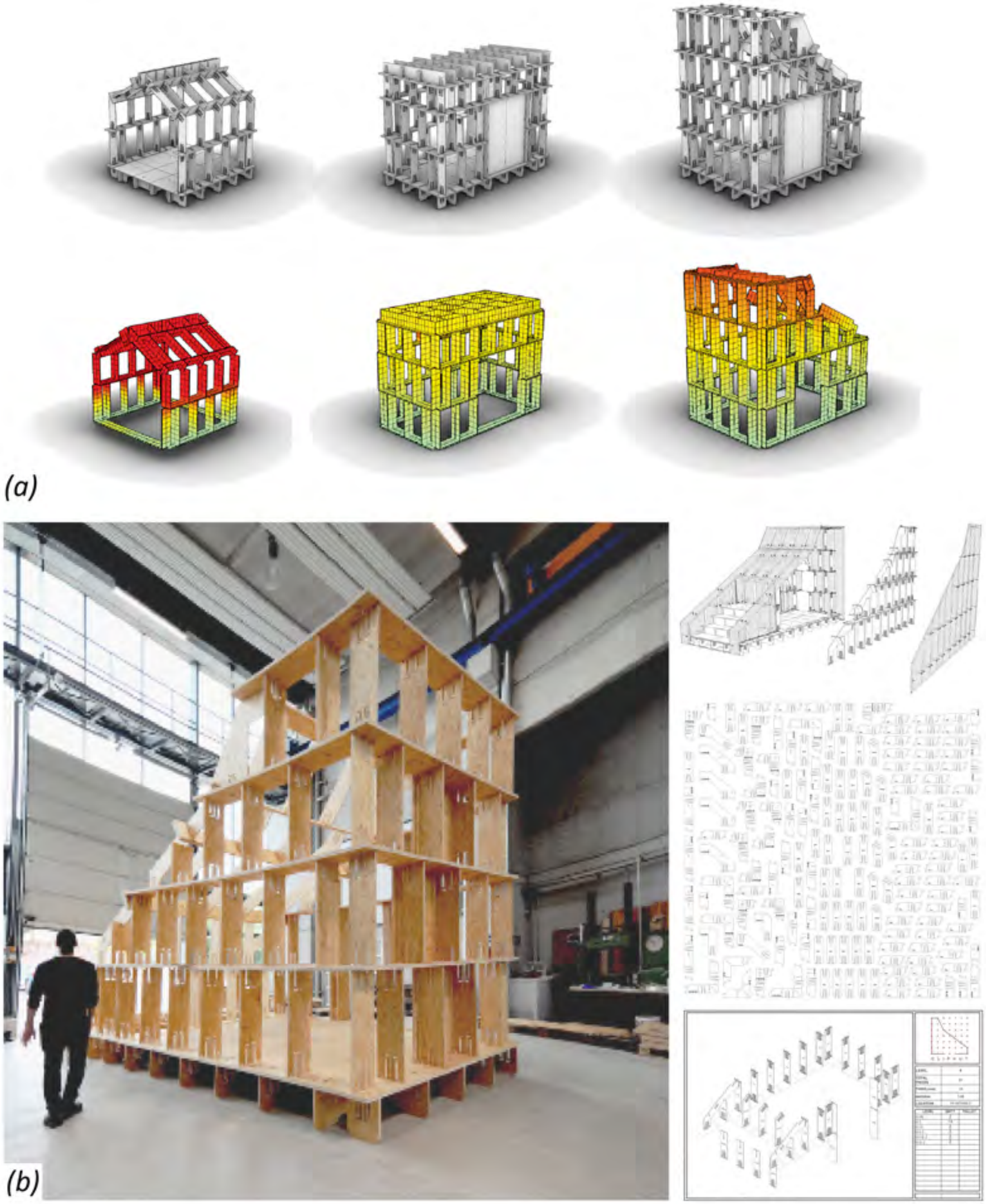

Figure 15
(a) FE Analysis (b)
Outcome

as a parameter, once the application was finished the function effort/time to generate a new model will stay almost flat (see figure 14a). Overlapping it with the popular graphic that compares BIM and traditional methods (see figure 14b), we can theorize the advantages of using such a framework within the scope of mass customization.

It is known that there are many plugins and tools at disposal, but no initiatives to formalize a method and a semantic. Understanding the difficulties in traditional processes is the way to locate the gaps during the design and construction processes. Acting in this way, not only relevance is attributed to the use of the method, but it also opens spaces for an interdisciplinary field that can contribute to close gaps between designers, society, and industry.

Although the research is still in its early stages, which implies the combination of many agents to have a fully automated framework, the results achieved so far show the guidelines for future investigations into the topic. Some of the consequences of this implementation may lead in a different direction, further expanding our perception of industry 4.0.

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Material Studies for Thermal Responsive Composite Envelopes

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The material-based studies examine through computation and physical prototyping layered composites for thermal responsive building envelopes. Focus is placed on surveying and computing a large series of materials across four groups, for then to test these materials from factors of solar energy reception capacities, internal heating methods, heat isolation coatings and layer bonding. An oak-polyethylene structure is developed based on the first studies and further tested towards implementation as part of an adaptive envelope demonstrator, with these studies focused on fabrication and assembly methods. Results of the developed, tested and applied composite as part of an adaptive envelope shows that the environmental-material composite is strongly influenced by colour and direct solar radiation exposure. This in turn allow a material-fabrication approach to program a responsive system driven by exergy. Reinforcing the responsive reaction of the composite by internal heating does not advance the performance, as coatings are needed to maintain the heat inside the material, which adds weight and isolate the composite from the thermal environment that otherwise is intended to provide the energy for driving the responsive behaviour. Please write your abstract here by clicking this paragraph.

Keywords: *Material Studies, Thermal Responsive, Composites, Building Envelopes*

INTRODUCTION

This work and paper are focused on how materials can be combined into thermal responsive composites. Through the focus on material properties, assembly processes and thermal energy distribution in the composites, the study contributes to new understanding of the thermal reactive performance of layered materials. In this way, the work is intended as foundational research for intrinsic responsive and adaptive architectural surfaces, which are driven by material-environmental properties and interactions, in contrast to extrinsic mechanically actuated systems.

Previous research on material based responsive systems can be seen by thermodynamic (Foged and Pasold, 2015, 2016) and hydrodynamic (Correa et al 2013, Reichert et al, 2015, Raviv et al, 2014) studies, where both direct (material as actuator and environmental element) and indirect (material as actuator of an environmental element) actuation is studied. For layered material responsive actuation, based on material differences in thermal expansion, studies (Foged and Pasold, 2010, 2015, 2016) have been conducted, and in industrial products the use of bi-metals is developed and used (Kanthal, 2008) as an actuator, typically used as triggers for an intended temperature indication, such as a boiling point.

The background on potential solutions of this work is a data collection surveying of a large set of materials to understand through computed combinatorial analysis the material responsive performance of a multitude of resultant composites. Additionally, increased understanding of connectivity between layers is important to utilise the composite's responsive properties. Bonding studies with different adhesives of material layers and internal/external heat activation of layers are studied to understand both fabrication constraints and environmental and system activation of thermal-based responsive composites.

The paper presents firstly the survey and computed combinatorial analysis of approximately 200 materials, across 4 material groups. Following the categorization and understanding of materials through computed models, ten materials are selected for physical prototyping studies, where composites are fabricated to investigate the physical bending when exposed to actuation under gravity and thermal gradients. Additionally, the paper illustrates how a selected composite can be applied in an auxiliary adaptive envelope and installed as an on-site full-scale demonstrator. This effort points to the potentials of combining material-environmental responsive structures with mechanical-microprocessor driven mechanisms for coupled response properties. Lastly, a discussion of the material studies, their relevant integration as architectural responsive surfaces and future outlook is presented.

METHODS
The study uses a hybrid approach of material surveying, categorization, combinatorial analysis and physical prototyping. Each method is a stepwise delineation and filter the research of responsive performance based on composition of material layers.

Material surveying
Material surveying is done via online portals and, most notably, the Material Connexion Library in combination with Granta's CES Edupack. Two principal values are extracted, namely the thermal expansion coefficient, alpha, (10-6 m/(m K)), determining the amount of expansion in relation to temperature change, and Young's Modulus, E, (GPa), determining the elasticity of a material. 193 materials are listed across wood species, plastics, metals and (other than wood) organic materials. Additional information is gathered for availability/rarity, sub-types of colours, densities et cetera. A similar survey is made of bonding materials, including acrylics, adhesive, liquid sealants, lockers and structural glues are included. The primary parameter assessed is the shear modulus, G, (N/mm2), as the shear force between layers may lead to delamination during asymmetric expansion of the composite layers.

Combinatorial Analysis Studies
Based on an ordered table of materials and their specific properties, a computed combinatorial analysis is made in MS Excel, computing all possible pair-layering combinations of the materials, resulting in bending properties, deflection from a plane (mm) and a graph representation, which visualise the resultant bending of the specific composite, figure 1. This is done by using the industry formula (Kanthal, 2008) for bi-metals, where in this case, geometric and temperature variables are constant, hence, the relative performance of material composites measured against each other.

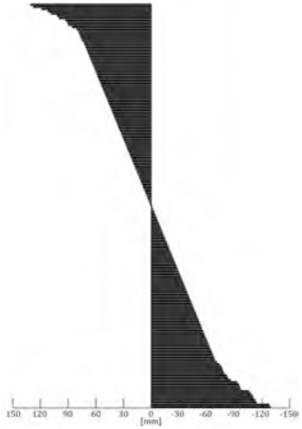

Figure 1
Deflection of composite materials are calculated as bi-materials, but consist in reality of more layers, including 1-2 binding layers, which effect the properties of the composite structure in terms of strength, elasticity and thermal conductivity. The responsive bending can be positive and negative in direction depending on layer composition.

Prototyping Studies

Ten materials are chosen for physical prototyping studies, including Oak, Walnut, Pine, Polypropylene (PP), Polyethylene (PE), Polyvinylchloride (PVC), Copper, Aluminium, Bronze and Styrofoam. The materials are then combined to study the adhesive properties between low and high energy surfaces, their response to heat change and how heat can be induced between layers to increase responsive performance beyond the temperature change created by microclimatic changes in proximity to the composites, as studied previously. A part of these studies are materials placed in the sun to measure the change of surface temperature as a result of solar radiation and material properties, which effectively drives the geometric responsive changes. This study gives an indication of the relative energy build-up in respect to material surface characteristics. As the study is aimed for potential applications in both indoor and outdoor environments, measurements were conducted outside to understand the minimum relative difference between materials, due to the added cooling effect of the materials from air movement. The study was conducted on a flat horizontal roof, with isolation between materials and the roof surface, in Copenhagen on 25 May, with a semi-cloudy sky, ambient temperature of 21 degrees Celsius and wind velocity of 4 m/s, figure 2.

In another sub-study the bonding of materials into composites are examined, through the testing of five different bonding groups, with variations in tapes with core, tapes without core and primers. Additionally, five different approaches to inducing heat between layers are tested, including heated copper mesh (0.5mm), aluminium mesh (0.5mm), copper wire (1 mm), aluminium wire (1 mm), kanthal wire (1 mm) and heat tubing (3 mm). The internalised heat source is controlled by a microprocessor (MCU) setup, which enable coupling to sensor information. Thus, potentially allowing linking of environmental sensor data, via an MCU with embedding decision taking, to the actuation of the composite by inducing heat through the wire, creating a full 'system feedback' responsive system setup. Following these studies, extended tests to increase the impact of controlled heating by mesh/wire/tube, experiments with wrapping the composites were done. These studies include cotton, wool and cotton/aluminium, wool/aluminium covers, where the temperature build-up is measured and compared to non-covered composites, figure 3.

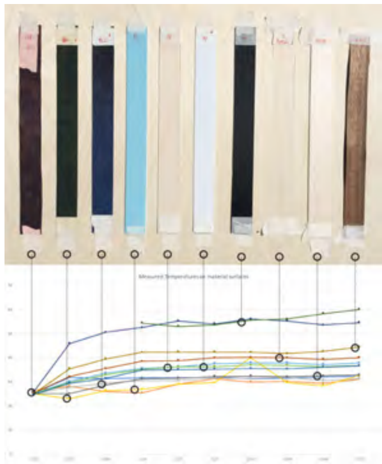

Figure 2
Graph of surface temperatures as a result of solar radiation and material properties.

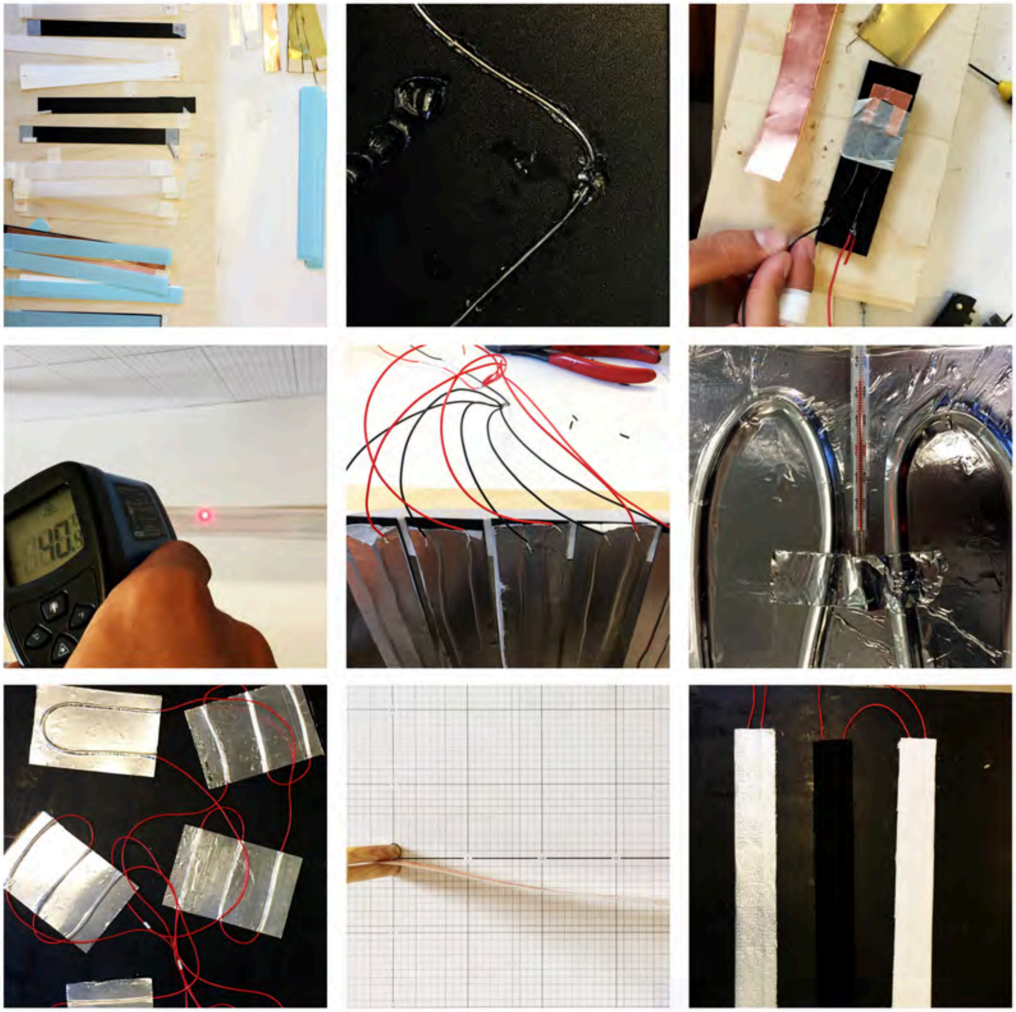

Figure 3
Prototyping studies for assessment of bending behaviour, energy transfer and energy conservation of the tested composites.

DESIGN EXPERIMENTATION

The experimentation with designing and making composites has been based on a project of creating a full scale 3x10 metre adaptive auxiliary building envelope. The focus of this paper, on the material studies for intrinsic driven responsive membranes, has been conducted in parallel to developments of a sensor-processing-actuation system and behavioural studies of the membrane-space-occupancy interactions. Due to the extent of the material studies and other aspects of the entire project, a full account of other aspects than the material studies are to be found in associated paper publications. Following the focus of the material studies in this paper, the experimentations described above where expanded to investigate cutting methods for the layer-assembled membranes. A series of material prototyping studies, as described above, revealed a high responsive bending performance and operational durability of the thin membrane (1.5 mm) when combining Oak (0.5 mm) and PE (1 mm). Oak has low thermal expansion parallel to the grain and PE has a high thermal expansion, as an isotropic material, in all directions. Combining materials with low and high energy surfaces require priming (3M Primer 94) the low energy surface to allow adhesion to the high energy surface through a non-core high bond adhesive 'tape' (3M VHB LSE.

The dimensions of the membrane responsive panels were developed through simulating the amount of solar energy passing through the composite membrane as a function of temperature variations, described and documented in the associated publication. The design experimentation of the material studies is then followed by investigating methods for cutting the generated membrane shapes, which ultimately becomes the material responsive elements of the envelope. For these studies, a Zund Eurolaser XL-1600 flatbed industrial machine is used with three different tool heads; a laser, a vertical oscillating knife, and, a 1-2 mm wide mill head. While the laser cuts through the composite (oak-glue-primer-PE), it melts the PE, which then 'travels' towards the oak layer and creates edges and surface on the oak with unintended plastic coating. Using a knife method allows clean cuts, particularly along the grain of the oak, but fails to create a small gap, which is required when the composite attempts to bend out of its plane during thermal changes. Without the gap, friction is caused, reducing or prohibiting the bending action. Using a 1 mm drill head creates both a clean, non-melted and friction less result. Only drawback with this method is the accumulated PE on the drill head, due to heated material, which may cause reduced cutting ability, leading to mill head fracture, figure 5. In addition, the application of a bonding adhesive without a core material, only including bonding material when rolled on, reduces fabrication problems, as only a minimum of material interfacing between the primary material layers are applied, figure 4.

Following the making of the composite panel, pattern cutting and integration into the mounting frames, onsite studies were conducted to understand and demonstrate the responsive performance of an exergy-based geometric bending of composite elements. The envelope panels are located on the inside of a glass pane, facing south-east, in a dense urban environment in Copenhagen. This means that the composites are effected by solar radiation on limited and specific hours of the day, that they are not cooled by air movement, and that they are embedded into an interior environment which ambient air is automatically kept at approximately 22 degrees Celsius from HVAC systems control. This means that the bending performance of the membrane is isolated to the solar radiation in relatively short and specified periods allowing a good reading of the solar radiation to material performance relations. As shown by the colouration/temperature studies above, dark materials have a significantly higher surface temperature, which increase response performance per degrees Celsius change. Hence, a black PE was used with the oak to form the primary material layers of the composite for the onsite demonstrator studies, figure 5, 6, 7 and 8.

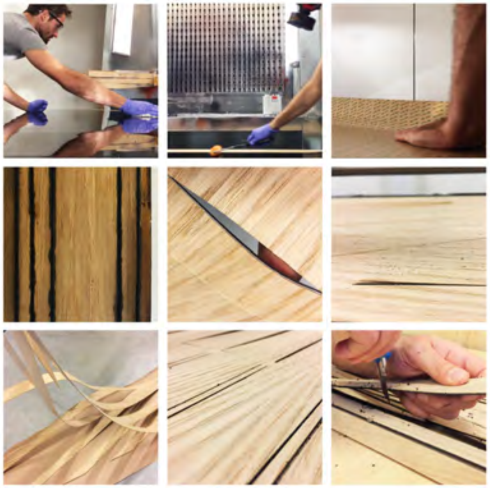

Figure 4
Testing of membrane fabrication procedures to allow material and geometric properties to be maintained and 'released'.

Figure 5
Full scale demonstrator with developed and tested thermal responsive composites in the Copenhagen School of Technology and Design Library. Left image shows the developed composite mounted in operable frames on the glass pane. Right side close-up of the composite bending and creating light permeability through the membrane.

Figure 6
Dynamic bending of the developed composite after approximately 3 mins of direct solar radiation exposure.

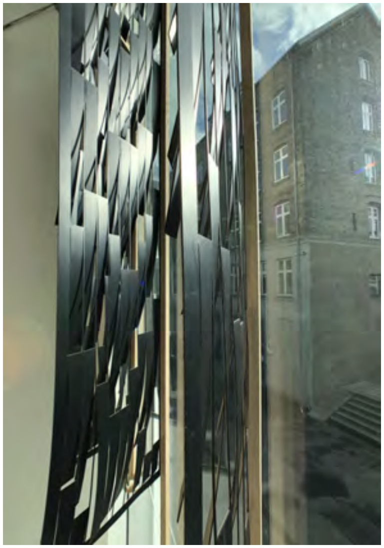

Figure 7
Black PE side of the composite with orientation towards the solar energy source driving the exergy-based responsive change.

Figure 8
Temperature measurements on the installed demonstrator. The shaded oak surface side is warmed to 36 degrees Celsius through the composite, with the black PE surface side measured to 57 degrees Celsius where the ambient temperature is approximately 22 degrees Celsius.

RESULTS AND CONCLUSION

The studies include a series of quantitative and qualitative results and conclusions.

- When solar radiation is the driver for actuation, colouration has a large impact on responsive performance. Comparative analysis measuring a range of materials show this, and measurements on the demonstrator support this, with the black PE side reaching 57 degrees Celsius, compared to the ambient temperature of 22 degrees Celsius. The specific degree of colour impact on performance is determined by the composite primary materials, the bonding structure, the geometric relations of size and thickness and the onsite explicit exposure to the solar energy.
- Coating the composites to increase thermal build-up by internal heating, significantly/-completely reduces the ability to drive the actuation through the solar radiation as an exergy-based strategy. In addition, the coating adds weight to the active composite, which decrease response performance due to the extra load needed to be moved by the active composite. Hence, a coating/isolation approach to the responsive system must be taken when developing composites for the specific purpose.
- The composites developed hold some resistance to composite response behaviour fatigue. More than 150 days after fabrication, the composites are changing bending form and no delamination has been detected of the +400 bending elements. While the composites have not been tested in a climate laboratory where temperature constantly is changed up and down under regulated conditions, the composites have been placed in windows where they have been exposed to environmental conditions similar to possible applications in practice.
- The responsive operation of the composite is silent. This is favourable in spaces where en-

vironmental sound levels are low, such as offices, study environments etc. Combined with the subtle and relative slow moment of the elements, the responsive membrane is perceived as a low-invasive active building layer.
- Given that the membrane is driven by solar environmental dynamics, it is limited to performance that are encoded into the membrane from its fabrication. Hence, such systems are not open to reprogramming of behaviour, which suggest the possibility of coupling to human and motorised systems, which may react to unforeseen or new conditions in a specific environment.

DISCUSSION

The presented studies contribute to the understanding and application of material driven responsive performance membranes, through a large material study and resultant catalogue of composite behaviours. It also illustrates how these can be bonded and cut into specified membranes reacting from thermal changes in an environment. The study also finds that additional activation of the responsive capacities through inducing heat between layers and insulating the composite to improve and maintain heat build-up are problematic. This is also due to the wire reducing bonding between layers, resisting bending (depending on wire layout). Further studies into internal heating and regulating of stimuli for responsive behaviour may however change the instrumentality of the responsive material system into a more open and adaptive operated system based on unknown conditions when the envelope is fabricated. Hence, this may be an option for controlling bending through an MCU with embedded behaviour controls, yet, enhancements of this approach through insulation of the composites also means isolation from the thermal microclimatic environment which activate responsive behaviour without applying electrical energy. For this reason, the study points to coupled, or hybrid, systems, where intrinsic material-driven response behaviour is paired with another response system, such as proposed in the general project, allowing material-driven and MCU-driven systems to operate in combination without limiting the capacities of each their specific strengths as environmental adaptive mechanisms for architectural envelopes.

ACKNOWLEDGEMENT

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A Framework for a Five-Axis Stylus for Design Fabrication

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This paper proposes a new workflow between design and fabrication phases through the introduction of a novel framework centered around a stylus that is tracked in real-time for five-axis by a single RGB-D camera. Often misconceived as a linear process, urgent reinterpretation of design and fabrication tools is discussed briefly. Similar to how industrial robots have become an enabler for fabrication process in the field of architecture and construction, the necessity for providing a similar tool that would reform the ``design'' process is underlined. A generic stylus is proposed with interchangeable operations which allows for intuitive, non-obstructive grasp of the user serves as the physical avatar that transform into a virtual representation of a fabrication tool mounted on a six-axis industrial robot arm. User interaction with the apparatus is simulated for the user, and the user is notified of any errors as the interaction is translated for motion planning of a KUKA KR20-3 industrial robot.

Keywords: *Human-Computer Interaction, CAD / CAM, Robotic Motion Control*

INTRODUCTION

Evolution of Tools for the Architect

As architecture evolved from its roots in crafts into its modern status, the tools employed by the architect and the architect's interaction with these tools have showed great diversification. This evolution marks the shift from an autographic practice in which the architect was exposed to the tools of fabrication, into an allographic system where the architect was expected to transform the data for fabrication into a notational structure through tools of abstraction. Mario Carpo pinpoints the exact time of the new definition of architecture's allographic and notational status to Leon Battista Alberti's theory and his treatise *De re Aedificatoria* (Carpo, 2011).

Alberti had strived to develop tools for exact reproduction through notational systems as evidenced both in *Descriptio Urbis Romae* and *De Statua*. No matter how detailed they are, there is an inevitable drawback inherent in all notational systems. Allographic tools can transfer only measurable data which can be encoded through a notational system. It contains a certain degree of abstraction in the making of the physical piece as data informed through the tools of fabrication is diminished in comparison to pre-allographic tools. A dichotomy is introduced in the process of making as the previously holistic process is remodelled into a linear two-stage approach in which, generally speaking, "design" precedes "fabrication". Status-quo adoption of Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) systems by the majority of architects in their workflow demonstrates that architects utilize these tools as to further the Albertian

Paradigm, deepening the chasm between these two stages as well as encouraging the ill-conceived linearity of design and fabrication.

A Hybrid Proposal

Appropriately used, digital tools can facilitate as a two-way link between design and fabrication. It allows to collapse the division between design and realisation as well as the distinction between intellectual work and manual production (Carpo, 2009). They allow the designer to tinker with the method of production closely, becoming almost like a prosthetic extension similar to pre-industrial craftsman and his pre-allographic tools. It fosters thinking through making, a method in which sentient practitioners and active materials can continuously correspond in the generation of a form (Ingold, 2013). Established properly, this reinterpreted interaction with digital tools can bolster the conviviality of these tools, an affinity towards familiarization and control of a production (Illich, 1973), which restores the bond between the designer, the tool and the fabrication. Designers can take comprehensive design decisions only as shortcomings in tools of abstraction can be recognized and the awareness of informing the process through the limits of tools for fabrication is raised.

The industrial robot is considered an enabler as it has industrially proven its ability to perform an unlimited variety of non-repetitive tasks reliably and providing the architect flexibility to inform robotic fabrication through architectural experience (Gramazio, Kohler, & Willmann, 2014). Albeit not strictly anthropomorphic, industrial robots provide a 6 DoF movement that can replicate the acts of a craftsman or a maker. Robot is merely a generic manipulator, and the emphasis is placed upon the manipulation of the material and the tool (the end-effector).

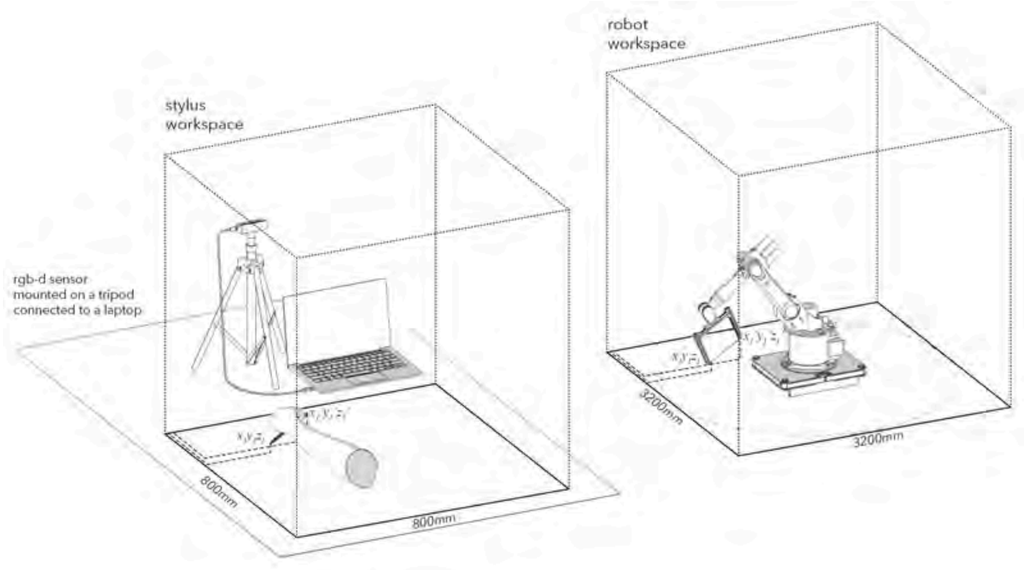
In a similar approach, a generic apparatus for the designer to mediate between design and fabrication is proposed. Through its genericity, it enables an intuitive grasp that is variant depending on the task at hand. Instead of serving a specific function, it molds into a virtual representation of any tool in a mixed-reality environment. As the designer takes design decisions utilizing this physical avatar which transforms into a tool for fabrication of his choice in mixed-reality, he intuitively can program a six-axis robot in the process as his motions with the apparatus can be translated for motion planning for the industrial robot. Fabrication feedback of the design is instant, and the designer can quickly reflect on his process and iterate the design.

RELATED WORK

Precedent attempts in mending design and fabrication stages with an industrial robot as a fabrication enabler in the field of architecture have primarily focused on understanding various crafts and translating the gestures of craftsmen, such as that of a stone mason (Steinhagen, et al., 2016) or a carpenter (Brugnaro & Hanna, 2017) to gather data to analyse and optimize the fabrication enabler for future processes. A previous study has focused on customized robotic tool path creation through a tangible controller that mimics an industrial robot (Payne, 2011), similar to puppeteering a scaled model. Even though they provide an intuitive motion planning for the manipulator, puppeteering and anthropomorphic teleoperation studies are disregarded as they do not resemble how a craftsman interacts with his tools and counter-intuitive from this point-of-view.

Tracking user gestures and translating them as user interaction is ubiquitous backbone of the field of Human Computer Interaction (HCI), and motion tracking is a mature field of research. Thus, the primary aim is not on the development of a novel technique in the field, but its implementation in the aforementioned context. Developed as a novel cost-effective active stylus tracking method (Bubnik & Havran, 2015), light chisel restricts the user to a chisel grip. Tracking of a stylus through a motion capture system, such as that of Vicon, is possible through the placement of custom markers on a target and their tracking. Although it is an established and precise method of an object, it requires an expensive

Figure 1
Proposed workspace for user interaction and its correspondent workspace for the industrial robot.



setup and is best for tracking larger targets. *DodecaPen* tracks an object with a monocular camera and the placement of 3D-printed dodecahedron with binary markers on an object, providing a precise tracking of a passive stylus with sub-millimetre accuracy (Wu, et al., 2017) and proposes a reliable methodology to work with in the future experimentations. Another method that can be integrated is the fusion of Magnetic, Angular Rate and Gravity (MARG) sensor and vision sensors for tracking the orientation and placement (Chintalapalli, et al., 2014). Even though most commercial HCI devices for mixed-reality environments are easy to get a hold of and tinker with, they are omitted from consideration as they come in a pistol grip form factor, a counter-intuitive scenario for a craftsman. zSpace, a commercial product with stylus interface working in tandem only with built-in tracking systems on dedicated displays which are viewed through custom glasses is neglected as a basis to develop the framework.

There is no prior study in developing an intuitive tool that links the gestures and the actions of the designer with a generic apparatus that serves as an avatar for a virtual tool for fabrication while translating data to form the motion planning of a six-axis robot.

SETUP

Workspace

An Intel Realsense D435 that utilize active IR stereo cameras as depth sensors is placed on a tripod on a table directly facing the user. Even though the depth camera can track objects up to a range of 10 meters, it starts to drift noticeably after a certain distance. Tracking of the objects within 30 centimetres also yield unreliable results. As such, the tracking space is limited within a distance of 30-110 centimetres in depth. For convenience, tracked space is also limited on a horizontal space of 80 centimetres and vertical space of 80 centimetres. Projected tracking space is indicated on the table. A laptop is placed next to the depth camera to provide visual feedback to the user. A six-axis industrial robot arm, in this case a KUKA KR20-3, with custom hot-wire cutter is used for the simulations and the fabrication. Tracked space correlates to the maximum reach of the specific robotic arm (r=1600 mm), corresponding to a 1:4 scale in conversion. The industrial robot is simulated as to be located at the center of the base plane of the confined space. **(Figure 1)**

Stylus Design

Design aim for the apparatus is to keep it as simple and as generic as possible, with the least amount of user guidance and material obstruction to accommodate a variety of holding and grasping gestures with an intuitive hold. Considering the stylus is expected to serve as a generic intermediary and as there will be no tracking of an active stylus, a *Caran D'ache Fixpencil 3* have been repurposed as the prototypical stylus body rather than designing and making a new stylus from scratch. This deliberate design decision also allows ease of mounting for interchangeable stylus tips. End cap and the stylus tips are custom color coded for tracking. **(Figure 2)**

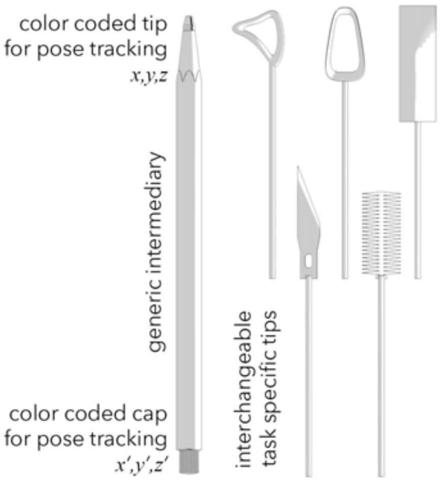


Figure 2
Utilizing the principles of a mechanical pencil, stylus is intended to have 3D-Printed tips that are interchangeable depending on the desired application.

APPLICATION

Initial test scenario for the designer to experiment with is (robotic) hotwire cutting of foam. Designer's interaction with the stylus is tracked and simultaneously simulated for robotic motion control on a screen. Location tracking of the stylus within the aforementioned workspace is achieved through object tracking by color using OpenCV. Center points for tracked color blobs are marked for pixel location in the RGB camera. Depth values matching these pixel locations in the stereo map are retrieved and appended as z-values for the marked locations. Realtime data is transmitted from a custom program to Rhinoceros 6 and Grasshopper.

Longitudinal axis of the stylus is defined by a vector through these points. In the case of robotic hotwire cutting, longitudinal axis of the stylus matches the wire direction that becomes the Y-axis of the end-effector. Midpoint between the tracked points becomes the tool center point (TCP) for the manipulator. Collection of these TCPs, which is intrinsically informed through designer actions, encapsulate the robotic motion path as the apparatus helps designate the tool XYZ coordinates and rotations around these axes. Robotic motion path and its immediate simulation is displayed on a screen utilizing the KUKA|prc plug-in for Grasshopper. User gets an error message in the case of out-of-reach, axis singularity or self-colliding solutions and is prompted to revise the input. **(Figure 3)**

RESULTS

As of this writing, there have been limited number of trials utilizing only the hotwire-cutting scenario. However, initial perception of the stylus is promising as an intermediary design input that is highly intuitive in terms of translating and informing designer actions for fabrication. The workflow establishes a practical link between the design and fabrication phases as intended and the visual feedback instantly informs the user regarding the actions taken.

Nonetheless, some imminent improvements are deemed necessary. The raw data needs to be filtered for jitter caused by the working principal of the depth camera sensor. Since this was a preliminary study to establish ground work for work to follow-up, the accuracy has not been a pressing issue. The workflow needs to be compared and tested against commercial motion tracking systems to prove its viability. As improvements in accuracy are implemented, correction for camera lens distortion should also be reviewed and accounted for.

It is noted that unexpected interaction with the stylus, grasping it solely from the ends, leads to obstruction of tracking due to utilizing a single depth camera as data source. In addition, rotations along the axis of the stylus - roll - cannot be tracked consistently. While this was not a problem in the case of hot-wire cutting application in which the affecting tool has perfect symmetry along its affecting axis, it should be resolved for other applications.

CONCLUSION AND FUTURE WORK

The research is an attempt at restoring the designer's association with tools of fabrication as well as reinterpreting the tools of abstraction. The new stylus is not a tool of abstraction nor a tool for fabrication - it is a new hybrid tool with both allographic and pre-allographic qualities as the dichotomy of design and fabrication is abolished. Physical articulation of embodied input and simulated output can enable a wider adoption of revamped technologies. Thus, future work will involve the comparative assessment of how the stylus and the workflow be adopted by different user groups ranging from novice design students to professionals.

Integration of an inertial measurement unit and utilizing magnetic, angular rate and gravity data is essential to increase precision to filter jitter in sensor data and provide additional data on the rotations of the stylus while tracked positions are obstructed. Furthermore, it will also permit the tracking of stylus roll consistently. Other stylus tips will be implemented and user interaction will be analysed.

Presently, only visual feedback is provided to the user based on the interactions. Inclusion of even the most basic haptic feedback for error notice is expected to enhance user engagement in the process.

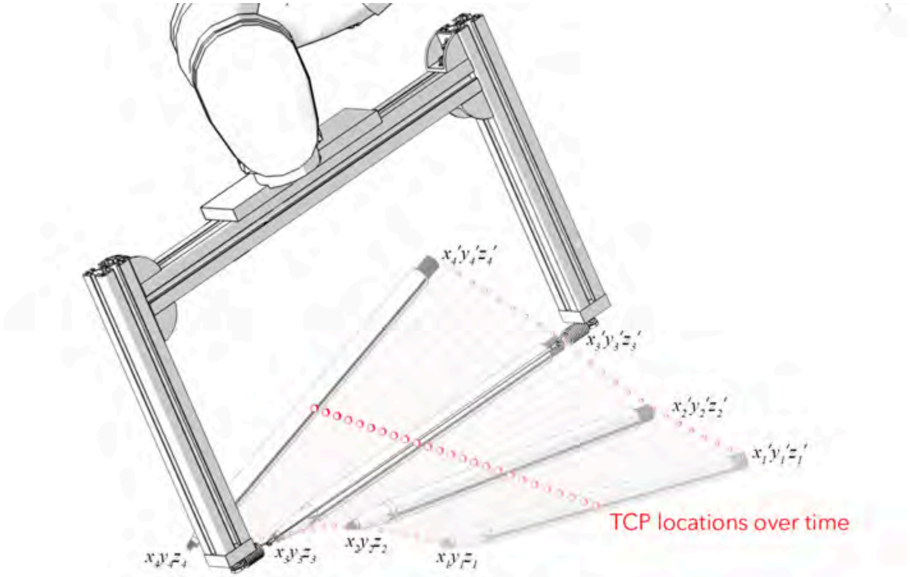


Figure 3
User interactions yield TCP location and orientation over time, which is used for motion planning for the robot.

Currently, all gestures are translated in a fixed scale. An intriguing aspect of a digital tool that blends design and fabrication would be its ability to surpass a confined scale and allow its user to experiment between different scales instantly.

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Data - BUILDING INFORMATION MODELLING 1

The Development of Architectural Design Environment for BIPV using BIM

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BIPV is a building integrated photovoltaic power generation system, which is used for building finishing materials, roof, and wall, so there is no need for separate installation space, and the usability is continuously increasing in urban areas with relatively small installation space. And continues to increase. BIPV is a building-integrated type, but the application plan should be made from the early stage of design. However, there is a lack of BIPV related design information. As a result, the possibility of integrating BIPV and building design is reduced and BIPV is applied in a limited range. Method: BIM-based BIPV design process, BIPV installable location, BIPV elevation design factor. And the theory necessary to implement the support model. Lastly, usability was examined using the support model. Result: This study describes a BIM-based design support model for BIPV installed elevation design that designers can apply BIPV installation location planning and design in a BIM environment.

Keywords: *Building Integrated Photovoltaic System , Building Information Modelling , Shadow Analysis , Array design*

BACKGROUND AND OBJECTIVE

Building integrated photovoltaic (BIPV) systems utilized in buildings substitute exterior finishing materials in roofs and facades of buildings with a PV module; they can also be used as cladding for buildings as well as electricity producing. The BIPV system is recognized as the most suitable system for the Korean environment that lacks open areas and has numerous high-rise buildings. Meanwhile, it is difficult for architects and builders, who lack specialized knowledge, to determine the suitability of BIPV system installation, which should be reflected in the initial stages of architectural planning and design, because its performance differs considerably based on the module type, installation type, and installation conditions. A solution for this is to merge BIPV systems with building information modeling (BIM) where the sequential application is possible through programming via design criteria rather than the intuition of an architect. This is also done to gauge performance based on the analysis of surrounding external environments and empirical data of the array design and BIPV system from its initial design stage. The objective of this study is the construction of a BIM-based

BIPV architectural design environment oriented toward architects who can creatively produce optimal BIPV design alternatives by accurately determining system suitability based on the above criteria.

RELATED RESEARCH

Building-integrated photovoltaics (BIPV) are less efficient than conventional solar photovoltaics, and studies have been conducted to find a solution to enhance the efficiency of the former. In a study focused on optimizing solar irradiation in the Hong Kong area, an investigation of the inclination and azimuth of the surface was done to achieve maximum BIPV efficiency, and BIPV installation angles and locations optimized for Hong Kong area were also presented (Fung, 2005). A similar study presented estimated annual power generation for different inclination and azimuthal angles in six major Korean cities (Seoul, Daejeon, Daegu, Busan, Gwangju, and Jeju) (Kim, 2014).

Improving BIPV efficiency by changing installation location and inclination angle have limited efficacy; thereby necessitating research on photovoltaic modules. A study verifying a module type adequate for architectural application based on analysis results of power generation performance data for a BIPV module, which was collected through an outdoor experiment on power generation characteristics by module type and installation angle, was conducted (Lee, 2016), Another research study analyzed the application status and module characteristics of BIPV systems installed in Korean public institutions in a case study (Eom, 2013).

BIPV is known to affect building appearance. To address the issue, research on semi-transparent cells has been carried out. In a study, comparison results of two modules with different transmissivities of module efficiency using semi-transparent cells showed that the module with lower transmissivity had superior power generation and thermal performance (Karthick, 2017).

One study has also been conducted in which design support software was developed for architects to lower the barrier in applying BIPVs to building design. In the study, photovoltaic system specifications and engineering and meteorological data were used to create a DB to minimize the condition input by the user and an evaluation module for the economics of photovoltaic systems based on analysis using the TRNSYS software. A developmental result of the performance analysis software for a grid-connected PV capable of BIPV integrative analysis was presented (Yoon. 2008). Another study obtained a meteorological analysis database for 162 regions in Korea and verified the validity of power generation performance for different design conditions including region, photovoltaic module type, installation location, and installation method using the existing commercial software PVsyst (Kim, 2015).

There are doubts regarding BIPV economics compared to existing photovoltaics. Research concerning BIPV economics include a study suggesting economical application methods by type with a comparative analysis of BIPV application methods available for residence type (Joh, 2006) and a study advocating the economic efficacy of BIPV through efficiency analysis of BIPV in houses (Noguchi, 2013). Another study arguing that BIPV is economical, which used the Life Cycle Cost (LCC) method to analyze the economics when BIPV was applied during the initial design stage of buildings, was also found (Bonomo, 2017).A study was found that investigated the effect of BIPV as an exterior material on building energy performance. In this investigation, a 5.25-kW BIPV installed on a building roof was monitored for its impacts on the building energy performance. Through a software simulation analysis of thermal conductivity and U-value, the study asserted that BIPV has a positive impact on the energy performance (Aaditya, 2017).

A design method to apply photovoltaics during the initial design stage of actual sites was proposed in Singapore. The design process was divided into three stages and eight design alternatives were evaluated using the Multi-Criteria Decision-Making (MCDM) method (Kosoric, 2011). A study of the design and application case of a zero-energy house using a photovoltaic system proposed a maintenance system optimizing building energy by applying passive design and a high-efficiency BIPV system to modify building energy load (Peng, 2017). One study developed a simplified method to readily predict the estimated amount of BIPV power generation during the design stage for different regions, module types, installation angles, azimuthal angles, and installation types (Choi, 2016).

Research on BIPV has focused on power generation efficiency and the energy efficiency of modules applied to buildings as well as analysis of power generation and economics with respect to shading, installation location, inclination angle, and azimuthal angle. However, few studies have proposed an architect-oriented BIPV system design by concretely applying the data of implementation results from shading analysis, array design, power generation prediction, and economic analysis, among other photovoltaic system design elements. It has also been shown that a feasible and reliable analysis tool applicable to a BIPV system is needed, and several studies have been in need of actual measurement data to improve BIPV system efficiency. The premises for precedent studies were module efficiency and technical challenge and calculation of power generation based on installation location in a building and module efficiency. They used various energy analytical tools capable of power generation prediction in a power generation simulation with different installation locations in a building (e.g., facade, roof, and shading shape) and installation angles and analyzed economical aspects by estimating the power generation amount. Numerous studies have been applied to actual buildings with BIPV to verify the system and data. However, a study integrating the architectural design stages for a BIPV system design is yet to be conducted.

EMPIRICAL DATA COLLECTION AND BIPV LIBRARY DEVELOPMENT

Testbed for data collection

To effectively predict power generation based on various environmental variables, it was necessary to collect comparative performance data of annual solar radiation quantities from inclination angles and azimuths for each region. Subsequently, a power generation calculation and comparative analysis were conducted using environmental conditions based on meteorological data by installing a mock-up. The test bed site is installed in Seosan-si, Chungcheongnam-do, Republic of Korea. The total floor area is 210㎡ and length, width, and height is 18.4m x 13m x 7m. The BIPV modules are installed on 5 sides on west, southwest, south, southeast, and east of the building. And the installation angles consist of 90, 75, 30, 15, and 3 degrees. The installed solar panel module is 120ea which is consisted of 60ea of crystal 160w module and 60ea of thin-film 100w. Figure 1 shows the picture of installed mock-up building and floor plan and section.

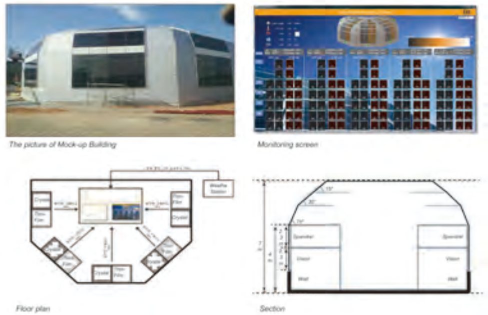

Figure 1
Testbed Mock-up Building

BIPV Library

The construction of a BIPV library first requires the establishment of parameter information items and parameter classification to record accurate information. In terms of an information model for the BIPV system, parameters are important factors that link correlations between the configurations of components and performance data extraction. The detail of the established parameters are:

- **Power generation analysis**: 1. Basic calculation formula according to the basic specification of the module, and 2. Calculation formula by Mock-up data
- **Economic analysis**: 1. New and renewable energy supply duty ratio = New and Renewable Energy Output / Estimated Energy Usage × 100, 2. Estimated energy usage = total building area × unit energy consumption, 3. Correction factor by application × Area coefficient, 4. New and renewable energy production volume = installation scale by source × Unit energy, 5. Production amount × correction factor, 6. Break-even point calculation (initial investment cost, annual power generation cost, and 7. Cost of replacing exterior materials, cooling/heating energy cost per year.
- **BIPV installation basic rules**: Installation Specifications
- **Legal review**: 1. New Energy and Renewable Energy Development Promotion Act, and 2. Regulations on support for renewable energy facilities, etc.
- **Solar cell characteristics information**: Module test report, module specification information, and supplementary material specification information
- **System Integration Company Information**: 1. Model name, manufacturer, manufacturer's phone number, manufacturer URL, and module insulation configuration, and 2. Frame configuration, and installation cost
- **Materials and Finishes**: Glass material and frame material
- **Module Information**: Characteristics, function, application, product shape, test report, and module product price
- **Building performance**: Power generation, efficiency, module configuration, specification of auxiliary materials, heat transfer rate, permeability, and details an Information
- **Size**: Vertical bar Vertical length, and vertical bar thickness
- **Estimation Factor**: Material cost, labor cost, and unit cost
- **Material Information**: Module insulation construction, double layer glass design, and Frame composition

Using the established parameters, a construction library was built with a G-to-G type multi-stage module that accounts for the majority of the BIPV systems, as well as two types of PV-crystalline structure (c-Si) and thin film (a-Si). Subsidiary materials constructed one type of module frame, six types of inverters, and eight types of connection bands. A BIPV library not only improves work efficiency and reliability among architects through the automation of company, performance, and estimate information, but can also reflect changing the information in real time. Figure 2. shows the libraries of the modules which has 3D model, elevation, and plan.

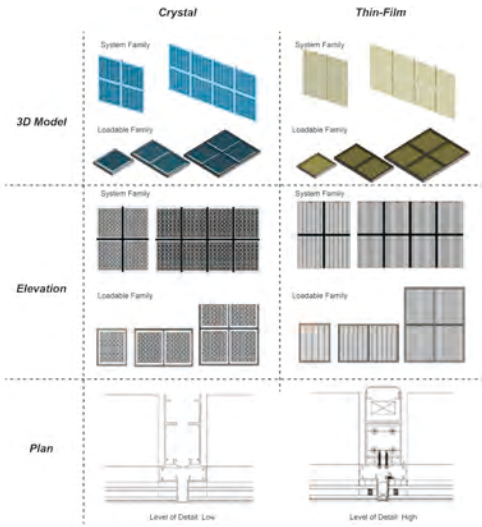

Figure 2
BIPV module library

Figure 3
Initial screen of BIM-based BIPV design application

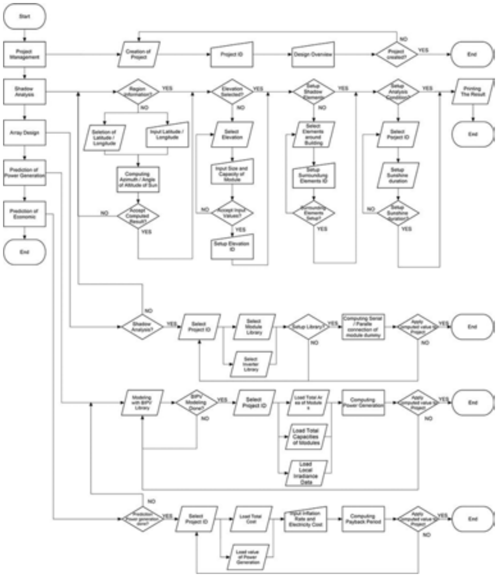

Figure 4
Structure of the program

DEVELOPMENT PROGRAM OUTLINE

In this research, BIM environment means using Autodesk Revit SDK. On the environment, the program for BIPV design support is developed with API supported by Autodesk. The program runs in the Revit 2008 and 2009 as add on program. The purpose of program is to support discover the optimal alternative of BIPV design for architectural designer with various information related BIPV.

The program can output the calculation results by directly extracting the data needed from the BIM model, systemizing BIPV material information, constructing digital material information, and improving reliability by connecting a prospective calculation algorithm from empirical solar radiation data. This program was developed by employing a shading analysis, an array design, power generation forecasts, and economic feasibility analysis algorithms. This provides meteorological data analysis, a PV design analysis, an analytic forecast, and a document creation function of the buildings targeted for design. Further, the analytic and forecasting function provides a shading analysis, an array design, and power generation and economic feasibility forecasts. Figure 4. shows the structure of the program and Figure 3. shows the initial screen of the program.

Until the simulation is finished, the results of each function remain in the memory and then the result of the simulation is stored as a database file. The result can be converted to report with the database file and stakeholders can share the result with the reports easily.

The test building for the program test is newly built testing facility in Chungbuk Innovation City in Korea. BIPV system, which is 33.652kW of capacity, thin-film and crystal module, is planned to install on the building.

Shading Analysis

One of the important factors in BIPV power generation performance is shading in the building surface. The shading analysis analyzes shading related sun movement, surrounding buildings, terrains. The using analysis method in the program applies the current solar view analysis technique to compute shading occurrence on the face of the target building. The shading analysis runs using to calculate the angle of altitude and azimuth of the sun, coordination of azimuth quadrant, and projection of the object

Setting elevation is required to analyze the BIPV possible installation area. In this step, The building faces general module size and faces grid is set and then the duration of sunshine is set as an analysis condition. After finish building elevation setting, surrounding objects should be set. Figure 5. shows analytical surface settings. In this setting, the parameters of the module can be set and the surface to analyze shading can be selected.

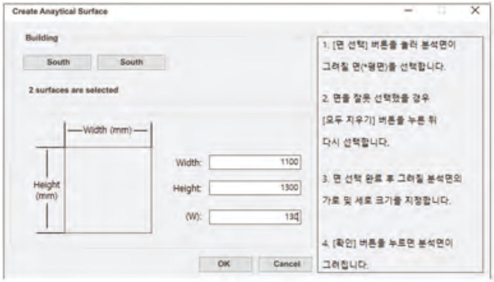

Figure 5
Analytical surface settings

In this program, the surrounding objects are neighborhood buildings. The buildings are called to Building 1 to building n. The shading elements converted to x, y, z coordination with the quadrant coordination convert formula. BIPV installation possible analytical surfaces are displayed with grid lines. If the color of grid lines is red, it means before analysis, unsatisfied to installation condition, or the faces are influenced by surrounding environments. If the color of the grid lines is green, it means the installation condition is satisfied. Figure 6. shows the visual result of shading analysis.

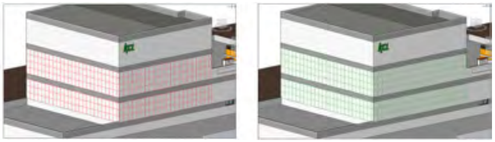

Figure 6
The result of shading analysis: left is unsatisfied, right is satisfied

Array Design

An architectural designer can decide BIPV installation capacity according to client's requirements using the array design. In this phase, the type of BIPV module, inverter, and connection board can be decided. The BIPV elevation design must be invoked complex factors which are the result of the shading analysis. If the relations with electrical properties of module and inverter is not calculated properly, dummy modules for only elevation design can be issued. The dummy modules don't generate power and the more dummy module the less power generation and economic feasibility. This program can help to arrange modules in the serial and parallel placement of modules optimally. The calculation of the serial and parallel placement of modules uses the formula of temperature anomaly on the surface of modules, the capacity, and voltage of module and inverter. the used formulas are:

$$t_{\text{max}\,d} = 25 - t_{\text{max}} \tag{1}$$

$$t_{\text{min}\,d} = 25 - t_{\text{min}} \tag{2}$$

where,

$t_{\text{max}\,d}$: Max temperature anomaly of modules
$t_{\text{min}\,d}$: Min temperature anomaly of modules
t_{max} : Max temperature of target location
t_{max} : Min temperature of target location

$$N_{S\,\text{max}} = \frac{Vdc}{Voc} \times \{1 + (V_{nt} \times t_{\text{min}\,d})\} \tag{3}$$

$$N_{S\,\text{min}} = \frac{Vdcm}{Vmpp} \times \{1 + (V_{ot} \times t_{\text{min}\,d})\} \tag{4}$$

where,

$N_{S\,\text{max}}$: Max number of serial modules
$N_{S\,\text{min}}$: Min number of serial modules
V_{nt} : Temperature factor of normal voltage of module
V_{ot} : Temperature factor of operation voltage of module
Vdc : Inverter max input voltage
$Vdcm$: Inverter min input voltage
Voc : Module normal voltage
$Vmpp$: Module operation voltage

$$N_P = \frac{C_I}{N_S \times O_{M\,\text{max}}} \tag{5}$$

where,

N_P : Number of parallels modules
C_I : Inverter capacity
N_S : Number of serial modules
$O_{M\,\text{max}}$: Max output of module

Figure 7. shows the screen of the setup module setting. in this screen, the thin-film module is selected and the detail specification of the selected

module can be checked. And Figure 8. shows the setup inverter setting. the selected inverter is transformer type and three phases 100kw(independence indoor). in the part, the detail specification can be referenced. The serial and parallel array analysis brings out the installation capacity, cost, BIPV production power amount, forecasting energy consumption amount, the duty ratio of green energy in the report. Figure 9. shows the array design report.

Figure 7
Setup module settings

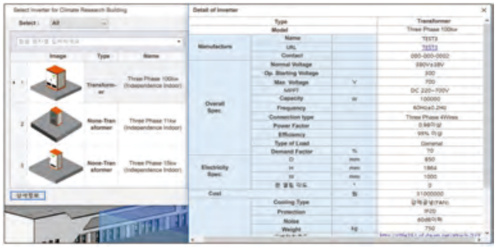

Figure 8
Setup inverter settings

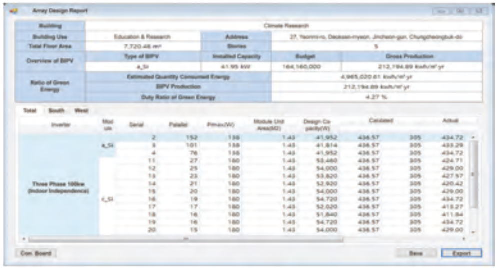

Figure 9
Array Design Report

Forecasting power generation

The decision of BIPV location for BIPV maximum power generation is required analysis and construct data of yearly accumulated irradiation gain performance comparison on the angle of altitude and azimuth of the sun. To do it, the mock-building is used as mentioned in previous. At the mock-up building, the values of Isc, Voc, Pmax, Vpm, Ipm, and FF of modules and irradiation, humidity, temperature, wind direction, and wind speed are measured and stored into the database daily. Figure 10. shows the result of forecasting power generation. With the data the formula of forecasting power generation is made:

$$E_{PMe} = P_{AM} \times \left(\frac{H_{AM}}{G_s}\right) \times K \times A \qquad (6)$$

where,

E_{PMe} : Forecasting power generation by the empirical irradiation

P_{AM} : Total installed area(m^2)

H_{AM} : Monthly or Yearly accumulated irradiation(kWh$/m^2$·month or year)

G_s : intensity of solar radiation(kWh$/m^2$)

K : Module efficiency(Tested average efficiency)

A : Modification Factor(0.78 applied)

$$E_{PMs} = P_{AM} \times hour \times day \times K[kWh] \qquad (7)$$

where,

E_{PMs} : Forecasting power generation by the standard test condition

P_{AM} : Total capacity of modules[kW]

$hour$: Power generation hour(applied 3.4 hours per day)

day : Power generation days(30 days per month, 365 days per year)

K : Module efficiency(average efficiency of the test grade)

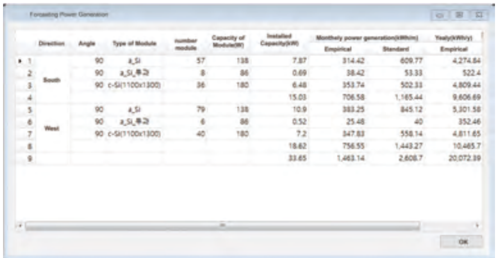

Figure 10
The result of forecasting power generation

Figure 9. shows the result of forecasting BIPV power

generation. In the forecasting, the properties of BIPV installation are 90-degree installation and installation on the south and west face of the building. The result shows monthly and yearly forecasting power generation in empirical irradiation base(equation 6) and standard test condition base(equation 7) by installation degrees, directions, and type of module.

DISCOVER DESIGN ALTERNATIVES

The developed program is tested in a practical design and construction project to apply BIPV. The project is façade renovation of Wolgae middle school which is located in Seoul, Korea. This project is part of the business to renovate façade of old school building ordered by Seoul metropolitan of education, Korea. During this test, the program has been tested from design to construction. The requirements of the business are focusing on the aesthetic aspect of school building so using the conventional solar module is not satisfied with the requirement. To meet the business requirement, the color solar module is required so the BIM library of the color module is modeled.

The target buildings for this project are the main building and sports center originally but the sports center was canceled after the simulation phase. Three façade design alternatives were created for the main building and the optimal design alternative was selected with consideration BIPV performance. The result of simulation shows the south face of the main building is the optimal direction to install BIPV with 756.49m^2 possible installation area, 520ea modules, and 52.9kW possible installation capacity. In comparison, north façade doesn't have possible installation area, east façade has 71% of capacity, west façade has 24% of capacity against south façade. In Figure 11., the detail is described.

Figure 11
The result of simulation of Wolgae middle school

The three façade design alternatives were shown in Figure 12. The alternatives 3 was selected as the optimal alternative because the amount of power generation is 16.6 kWh and the total annual amount is 18.067.5kWh. The power generation of alternative 3 is 6% bigger than alternative 1 and 42% greater than alternative 2.

Figure 12
Design alternatives for Wolgae middle school main building

Figure 13
The comparison of before and after renovation

After the design phase, the construction with the optimal design has done actually. Figure 13. shows before and after the renovation of the building façade. It is one example of using color modules for BIPV.

CONCLUSION

Using a BIPV library based on the developed BIM, it is possible to automatically calculate installation capacity, initial investment costs, renewable energy output, and expected energy usage during BIPV design. Even architects with no experience can predict power generation based on various installation conditions and can quickly and simply determine system suitability in the design stage. In the BIM model, the solar radiation results of the standard test condition theoretical equation and the power generation comparison results of installation angle and installation direction using solar radiation field measurements showed an average error rate of 21%. Further, based on the incline, errors observed were higher for vertical predictions compared with horizontal predictions. Accurate quantity estimation based on a BIPV library that uses BIM produces accurate baseline data. Order management for primary resources and materials is possible using BIM, and this can be connected to job site processes and managed.

ACKNOWLEDGMENT

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A-BIM: A New Challenge for Old Paradigms

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This paper is the result of a pedagogic proposal applied to undergraduate students of architecture in order to present new digital design tools and methods. This study aims to connect procedural contents to different design strategies enrolled by students with special focus on complex geometries. The objective was to offer the necessary assistance to an appropriated design development, by reducing the habitual mishaps related to the lack of technical skills with digital tools for both the design reasoning and the subsequent graphic representation of proposals. As an answer, a new design approach called A-BIM (Algorithmic-based Building Information Modeling) was introduced to students, which integrates BIM platforms with algorithmic modelling software allowing, in this way, some formal flexibility allied to an adequate graphic documentation.

Keywords: *A-BIM, algorithmic design, BIM technology , parametric software*

The teaching and learning processes of architectural design undertaken by educational institutions is extremely diverse. Even though the usual tripod - theory, practice and instrumentation - is present in most schools, there are divergences of approaches between them. Among the many design tools available in the instrumental context, the digital ones are those undertaking a faster pace, modifying, according to Kolarevic (2003), architectural practices in ways that would be difficult to imagine decades ago.

Graphic representation is the means by which architects and designers engage in a reflexive conversation about a given design problem(SCHÖN, 1983; DO e GROSS, 2001; LAWSON, 2011). In other words, it is the environment where ideas flow from the mental world to the real world, allowing for a greater clarity of reasoning, but also a certain degree of ambiguity(OXMAN, 2002), which are necessary characteristics for new ideas to emerge from the analysis and iterations made with these drawings. Therefore, graphic representation occupies a central position in the creative process of architects and designers.

According to Mitchell(2008), architects often create implicit design worlds through their choice of drawing instruments and representational media. These design worlds, in turn, can be elaborated in different ways using various techniques and methods. In architecture, it can be seen that the most common techniques currently used are physical models, manual/analog drawings (sketches) and computational drawings and models.

Also according to Mitchell, each media has its axioms , that is, intrinsic rules that are relative to each technique of graphic representation, those that are inherent to it. For example, a design world created by a drawing made with pencil and paper allows a fluid trait and quick ideation, however, the representation is made one view at a time and in a two-dimensional manner. On the other hand, when using representation software and digital graphic modeling, architects are able to obtain the complete volume of the architectural object, allowing multiple views simultaneously. On the other hand, it can be limited by the scope of the programming methods of each software, thus hindering creativity. It is necessary, therefore, to know the axioms and limitations imposed by each representational media used.

From the emergence of Computer Aided Design (CAD) technology to its popularization between architects, engineers and designers, there have been transformations not only in technology but also in society´s life, making design practice increasingly intertwined with computational technologies as can be seeing in Weisberg (2008). At the end of the first decade of 2000 in Brazil, while Orciuoli (2010) claimed that some architectural schools still looked suspiciously upon the digital, Barison and Santos (2010) emphasized the appropriate moment to introduce parametric software such as the BIM platform (Building Information Modeling) in the undergraduate architectural curriculum.

Nevertheless, there are scholars that focus on the challenge of formulating an appropriated digital design framework in order to bring even more advanced technologies such as algorithmic and parametric visual programming associated with rapid prototype technology, as seen in Sass and Oxman (2006) and Sedrez and Celani (2014). According to Romcy (2017), in Brazil this paradigm shift is occurring at a slow pace, and only a few architecture schools have recently adopted programming disciplines in their curriculum.

In this scenario, Sofia Feist (2016) claims that the A-BIM technology - a combination of algorithmic processes with the BIM methodology, can offer many benefits to the architectural design process. According to Ruschel (2014) and Wahbeh (2017) connecting the formal freedom of algorithmic design to the standardized control of BIM, could be a best combination for a creative flexible information model.

Corroborating with the advance of this new paradigm to architectural design education, this paper presents a case study developed as part of a Master´s Architectural degree thesis presented in 2018. The main objective is to implement and analyze the use of an integrated A-BIM (Algorithmic Based Building Information Modeling) technology applied in an intermediate undergraduate design studio at a Brazilian Architecture School.

METHODOLOGY

Since 2017, the curriculum of the Architecture School of the Federal University of Rio Grande do Sul (UFRGS) has been undergoing a transitional period from a CAD to a BIM platform (the BIM platform Archicad is taught in the 3rd semester in the discipline of RGII). In order to fully understand the school´s curriculum, this research started in the first semester of 2017. By then, an analysis was carried out in two disciplines, one instrumental and the other a design studio, aiming to understand their dynamics and pedagogical approaches. This facilitated the study of possible focused interventions to introduce algorithmic modeling software and its interlacing with the BIM platform.

To participate in this study, in 2017 two undergraduate disciplines of the fourth semester were strategically chosen. They were Graphic Representation III (RGIII) and Architectural Design II (P2). The former is responsible for developing in the students both manual and digital skills while encouraging their ability to analyze architectural design; RGIII also has in its pedagogical history the tradition of teaching hybrid graphic representations, corresponding to part of the student´s computational instrumentation and graphical representation with analogic, digital and prototyping resources. The latter, P2, besides being responsible for the design practice, also has the capability of integrating knowledge acquired during the fourth period; a fertile ground where these experiences can be directly applied.

During the actual experiment, in the second semester of 2017, the RGIII discipline (one class, 45 students and 3 professors) was specifically dedicated to enhancing the students with the instrumental ground needed for a potential paradigm shift in their architectural design projects. The P2 design studio C (one professor and fourteen students), on the other hand, was the design class selected because of its pedagogical approach, which employs initial abstract conceptual explorations and their metaphorical symbols to compose the formal proposals of the student´s architectural designs.

The pedagogical interventions proposed in both disciplines presented the students with exercises that enabled them to explore the interface between a process previously unknown to students - the creation of algorithms in Grasshopper software and manipulation of the resulting objects in a BIM environment using Archicad software. Thus, while the RGIII discipline focused almost exclusively on the instrumentalization of students with the Grasshopper algorithmic and parametric platform, P2 encouraged them to use that platform in the development of design proposals in order to obtain greater freedom in formal and conceptual exploration.

RGIII

In RGIII, the exercise proposed was to model a building with low geometric complexity, but totally parameterized. In that way, it would either be possible to control the level of complexity presented, while at the same time benefiting of parametric reasoning in a context closer to reality (Figure 1). The parameterized model developed was a small shelter using woodframe constructive technique, in a way that the knowledge acquired could be used in the P2C class.

The exercise started by describing a profile of parameterized edges with their dimensions regulated by standards inherent to the constructive and modular system in woodframe. This profile served as a generator of the initial building volume, this way it was possible to construct, from the beginning, a reasoning that respected the modulation of the proposed constructive system while having the formal flexibility both in the initial profile and in its longitudinal dimensions, which are described later.

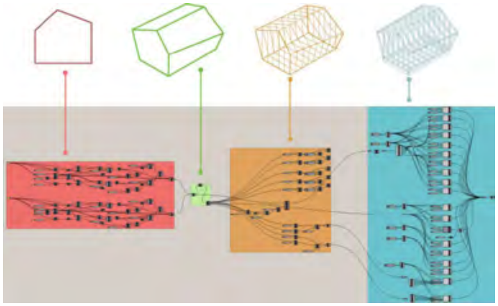

Figure 1
Explicit algorithmic reasoning

In the second stage of the exercise, a loft operation with modular distance was performed between two profiles, which had the same algorithmic description, but with different parameter values, generating in this way a volumetry that connected profiles with varied morphologies and generating non co-planar surfaces. Then with the defined volumetry, transverse and longitudinal sections were drawn with regular spacing according to a modular woodframe system. In this specific case the building volume was sectioned every 60cm, in order to obtain guidelines for the structural parts. From these lines, structural profiles with dimensions described algorithmically according to the position, size of the span or structural function were incorporated, following the woodframe construction guidelines indicated by Thallon (2008)and Ching(2016).

These structural profiles were incorporated into the guidelines using A-BIM technology. In this study, the "Grasshopper Archicad Live Connection" (GALC) plug-in was used to integrate algorithmic software into the BIM platform, allowing the insertion of native constructive information of Archicad into the abstract geometries generated by Grasshopper. In parallel, these geometries were transmitted in real time to Archicad, so it was possible to obtain graphical technical representations such as plans, sections and elevations, or even more complex details.

At the end of the process, it was possible to demonstrate to the students the resilience of the proposal presented when determining dimensional changes in both the generative profiles and the longitudinal dimensions of the volume as a whole. It was also possible to realize that the structures described algorithmically were able to correct themselves to the new positions and dimensions automatically (Figures 2, 3 and 4) at the same time as they were transmitting the new volume generated for the BIM platform.

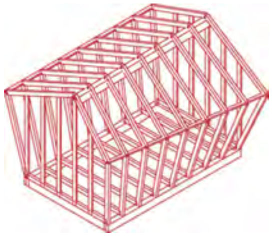

Figure 2
Initial Loft Structure

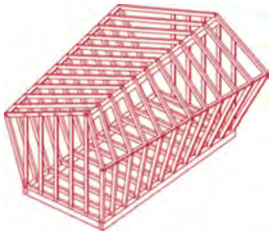

Figure 3
Loft Structure 02. Changes in profiles and volume dimensions

Figure 4
Loft Structure 03. Changes in profiles and volume dimensions

Furthermore, video-classes were made available to the students on the Internet containing more complex operations than those performed in class, complementing and stimulating the learning of parametric tools in different contexts applied to architecture.

P2C

The work developed in P2C consisted of the design of a small building employing woodframe construction technology. The theme of the project was a design hotel located outside the urban perimeter of the city of Porto Alegre-RS with a strong tourist appeal and fully integrated with nature. One of the main premises of the discipline was to connect conceptual ideas to practical solutions using design thinking techniques, proving to be a propitious discipline for formal exploration with a strong focus on conceptual design.

According to Laura Garcia (2012), design thinking uses inductive logic, admitting that it is impossible to attest to a new concept or idea in advance without first observing the development of future events. Thus, design thinking differs from the conventional approach used to solve problems because it helps in the exploration of new knowledge.

During the design concept and formal studies, the algorithmic platform was presented as an alternative media to the class. In this sense, specific interventions were suggested at key moments of the design process, with the aim of providing a possible digital focus during the students' creative thinking.

Added to the project discipline schedule were lectures on generative systems and parametric architectures applied to architecture, landscaping and urban planning projects. These classes served to instill students' curiosity about the suggested design strategies as well as provide a theoretical background to assist them throughout the creative design process developed during the semester.

One of the stages of the discipline provided for the creation of a graphic symbol that would synthesize the concept of the hotel. This synthesis-form could serve as an icon, a mark or a symbol of the project and had the purpose of translating into simplified graphic elements the concepts expressed hitherto mostly in textual character, articulating the concept to form.

Starting from this synthesis-form, theoretical and practical classes were undertaken before the launch of the architectural concept of the building, presenting concepts related to shape grammar. Thus the students could become familiar with principles such as atomic elements, systems and vocabulary of forms. Next, an exercise was suggested to use these concepts in practice. It was suggested that to the students to deconstruct their synthesis-forms into atomic elements, and to recombine them using formal operations derived from shape grammar, such as symmetry, rotation, translation and deformation, among others.

Students had the freedom to perform these operations in an analog or digital environment. In order to perform the exercise in a digital environment, algorithms were produced in the Grasshopper software in a way that the students could manipulate the atomic forms or sets of elements and generate combinations from symmetric or recursive formal operations, both two-dimensional and three-dimensional.

The main purpose of the exercise was to introduce a playful process of formal exploration into the digital environment that generated a wide variety of options, while keeping the synthesis-form elaborated by the students and maintaining the coherence with concept defined in previous stages. This way, it was possible to observe a great variety of formal options on the same architectural concept (SOUZA, 2018).

Among the 14 students enrolled, 4 of them choose to keep on exploring the algorithmic environment according to their project´s formal and technical complexities. These students, for classification purposes, were designated as T3 while the others as T1. In order to deal with the formal complexity of the architectural concepts developed, the modeling methodology of RGIII was used and improved (figure 5). This methodology was separated into 5 steps, of which, 4 modeling and 1 detailing.

1 - Surface Modeling (Rhinoceros 5 + Grasshopper);

2 - Guidelines Description (Grasshopper);

3 - Structural profiles Description (integrated Archicad);

4 - Modeling of the closing surfaces (integrated Archicad);

5 - Detailing and final graphic representation (Archidad and/or other software).

By analyzing figure 5, only a small part of the design process represented the core of formal exploration. Thus, the students were able to describe complex shapes using few surfaces or primary lines with the rest of the process adapting to these in an algorithmic way.

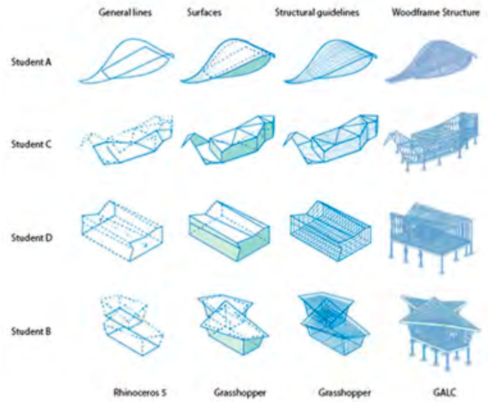

Figure 5
Modeling Process - T3

RESULTS

At the end of the semester, different types of data were collected and analyzed in an attempt to better understand the design process and to verify if there was a positive contribution by the interventions made in the targeted by the students, the data collected consisted of photographic records, class notes, student testimonials, and semi-structured interviews via Google Forms.

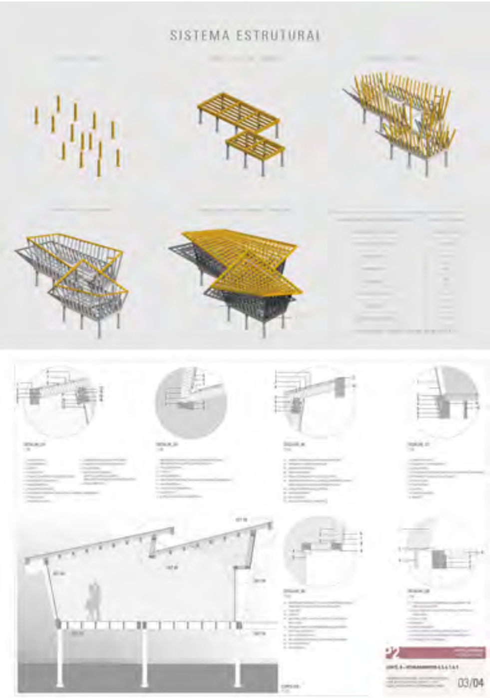

Figure 6
Modeling Process - T3

By presenting another possibility of project investigation, the results demonstrated that the T3 student group could successfully visualize the geometric relations during form generation and simultaneously obtain the architectural documentation needed for technical purposes (figure 6).

Corroborating with the previous findings, it was possible to observe the topological complexity achieved by T3 students revealing a clear difference between forms developed by students T1 and T3. In the T1 category, mostly orthogonal prismatic surfaces were employed, developing simple formal operations such as addition, subtraction or extrusion. On the other hand, T3 students chose to work with non-coplanar surfaces, tessellations, and "lofts" between different profiles, generating more complex forms than those from T1 group. Even though its differences, all students were able to reach satisfactory levels in their designs.

This experiment also indicated problems to be further analyzed and solved in future proposals, starting with the overall difficulty presented by the lack of intuitiveness of Grasshopper. Comparatively, this software takes a completely divergent approach from others most commonly used by students like SketchUp, Autocad, Archicad or Revit. In order to overcome this difficulty, constant monitoring was necessary as well as the production of complementary pedagogic material in order to enable T3 students to successfully finish their proposals (SOUZA 2018).

Another difficulty observed during the research was the presence of some issues in the data transmission between Grasshopper and Archicad using the GALC plug-in, amongst those, the following:

- Alignment Bugs: Alignment errors between profile and tabbed lines often occurred with divergence in the transmission of data from the position of some parts of the woodframe structure in Grasshopper to Archicad.
- Problems in the formation of complex surfaces with the "Shell Ruled" tool: this tool proved to be too limited to generate surfaces that did not have parallelism on at least one axis which proved to be insufficient for some proposals. To overcome this problem it was necessary to use several layers of "morph" surfaces.
- Interruption of the model update: The update generated in Grasshopper and transmitted to Archicad was interrupted frequently, making it was necessary to delete the model and then restart the connection.
- High hardware consumption: High consumption of hardware was noted, even in powerful computers, so this approach had a limited scope due to financial resources, making it less democratic.
- Unidirectional Workflow: The T3 category students were surprised by the unidirectional workflow of the plug-in. They would rather work with a bidirectional flow, which could

enable them to update the algorithm through the direct manipulation of geometry components.

However, in spite of the problems faced, the proposed methodology proved to be flexible allowing different levels of software knowledge during the design process as we can see in figure 7. This way, even students with little instrumental skills in one of the programs used in this methodology were able to complete their creative processes and their respective graphic representations at the end of the semester, allowing them to overcome typical software limitations.

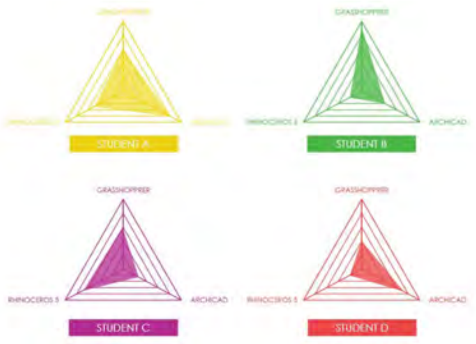

Figure 7
Diagrams with the different approaches undertaken by T3 students

DISCUSSION

The aim of this research was to contribute to the enlargement of students' design capabilities at a conceptual and formal level while employing a constructive system based on strict constraints such as woodframe. By combining experiences of creating and manipulating forms with algorithms to construction techniques and that of representation and documentation required in design disciplines, we seek to encourage the student's exploration of new design processes.

In order to do that, this research sought to delineate a divergent design process, by offering thru A-BIM a more continuous design workflow. This way, by minimizing software migration during the design process of T3 students, this research allowed the development of complex forms even using a restrictive constructive system that has rigid rules such as woodframe.

Also, by analyzing the final results developed by T3 students, it was possible to verify the cognitive and procedural benefits, as well as the methodological difficulties, and limitations inherent from the use of these technologies in innovative teaching methodologies. In this way, the study claims to contribute to future experiments, mapping new research possibilities and pointing out technical issues to be solved in the implementation of these design techniques with students.

In conclusion, it was possible to verify that the integration between the BIM platform and algorithmic/parametric software constitutes a favorable environment to stimulate creative reasoning, as well as to facilitate the graphic representation of complex forms conceived in the parametric digital environment, as long as a suitable base is provided.

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Interaction with analysis and simulation methods via minimized computer-readable BIM-based communication protocol

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The early stages of building design are characterized by a continuous endeavor for the development of variants and their evaluation and consistent detailing. The concept of adaptive detailing aims to enable the architect to evaluate and compare design variants which are partially incomplete and vague (Zahedi and Petzold 2018b). This paper discusses a minimized communication protocol based on BIM, which enables computer-readable interactions between the architect and different domain-experts (representing various analysis and simulation procedures) (Zahedi and Petzold 2018a). This comprises the selection of simulation procedures as well as any necessary consolidation of the information content according to the requirements of the simulations. Any additions required on the part of the simulation procedures are visually prepared globally or space-and component-oriented respectively, in order to perform detailing of a building model in a targeted way. Moreover, this paper proposes various supportive methods for visual representation and exploration of analysis results.

Keywords: *Building Information Modeling (BIM), Early Stages of Design, Adaptive Detailing, Minimized Communication Protocol*

INTRODUCTION:

Early stages of the building design are particularly important since decisions made in these phases will significantly determine the performance of the final building. More importantly, as the design process proceeds any changes to the decisions made in the early phases will impose extra costs and time loss on the project budget and schedule. As we move on from conceptual and early design phases into more detailed design, the ability to impact design will decrease dramatically while the cost of change will increase intensely (MacLeamy 2004). These early phases are also characterized by a continuous effort to create design variants, evaluate them and continue with their detailing. For the evaluation of design variants, the designer uses different criteria such as the owners' requirements, building performance, and cost. Objectifiable assessments like simulations and analytical procedures in early design phases are currently only used in part or with great approximations in model details and uncertainty involved with the results. The reasons for this are the insufficient process integration of supporting software solutions and the required model quality for accurate results that are lacking in early design phases. Some overall approximate simulation tools exist for these early phases of design, but their results contain mostly high uncertainties and additionally, in some cases, these analytical methods may have taken some simplifications and assumptions into account that the architect is unaware of them.

The Architecture, Engineering, and Construction (AEC) industry is among the largest industries in the world while having a unique nature that puts a high demand on communication and collaborative work. Communication and collaboration play a significant role in the effort to improve building design activity. Building information modelling (BIM) in its nature pursues the gaol to integrate and manage all the semantical and geometrical information related to construction projects. This feature in BIM enables new possibilities for exchange of information in digital format between different actors, such as architects and consultants, in a construction project. Thus, improving the access to computer-aided analysis from the early stages of design (Borrmann et al. 2018). The downside to this approach is that the planning effort and the sheer load of design decisions are shifted to the early stages of design too. Thus, leaving the designers to decide on so many details early on while they are not yet sure about them. This could also be seen as if the system forces these details on the architect with little knowledge about their consequences (Zeiler et al. 2007).

In other words, the main problem with these critical early stages of design is that in most cases concerning design decisions, the architect hasn't made his mind yet. It means that for every design decision, there exist so many choices and options, which the architect is either unaware of them or of their effect and consequences on the final design's cost and future performance. In addition to that, the architect is not and cannot be an expert in various fields of analysis and simulations that are needed to evaluate different design variants. This necessitates the need for asking different domain-experts and consultants to assist and support the architect in his design decisions. The research project EarlyBIM (funded by the German Research Foundation (Deutsche Forschungsgemeintschaft) under the grant number DFG-FOR2363) is devoted to the development of methods for adaptively detailing the partially incomplete and vague building design models in order to assess and compare different design options.

STATE OF THE ART

Facing numerous decisions during the important early stages of building design, the architect must make compromises since many design objectives are conflicting due to their dependency on each other. The process of Decision-making in building design has been investigated by many researchers using the Multiple Criteria Decision Making (MCDM) approach. Two methods are used to solve MCDM problems, namely Multiple Objective Decision Making (MODM) and Multiple Attribute Decision Making (MADM). Simply stated, in MODM the designer ends up knowing what ideal design variant he aims for and in MADM he finds out between a limited number of alternatives which one he likes the most. For example, Jalaei et al. proposed a solution to integrate a Decision Support System (DSS) using MCDM with BIM to support the designer in choosing the optimum sustainable building components (Jalaei et al. 2015).

Despite the insufficient information available during early design stages, BIM models appear precise and explicit. This may lead to false assumptions and assessment. Abualdenien & Borrmann introduced a Meta-Model for incorporating the inherent fuzziness involved in geometric and semantic information of individual building elements during these early stages. They also introduced a new concept called Building Development Level (BDL), which describes the maturity of the overall building model (Abualdenien and Borrmann 2019). This paper uses the BDL concept in order to specify the information requirements with respect to building elements and their maturity to carry out a model analysis. These adaptive information exchange requirements are called aLODx in our minimized communication protocol and are defined based on the above mentioned multi-LOD meta-model. An aLODx acts as an adaptive lookup table or translation table to which both the architect and domain-expert will refer when communicating based on our minimized communication protocol (Zahedi et al. 2019).

Considering the importance of collaboration and internal communication between different actors involved in building design, BIM Collaboration Format (BCF) was first introduced in 2010 as an open standard to enable BIM-based workflow and communication between different parties and different software vendors. Using the BCF, the project participants create topics (such as issues, proposals, and change requests) that contain various attributes like type, description, and comments. Each topic will be linked with a model element as well as a viewpoint and possible screenshots. This eliminates the need to exchange entire bulky digital BIM-models between software applications. (buildingSMART 2017) However, BCF XML is dominantly used for gasping human-readable data regarding issue management. Even though BCF v2.1 is capable of encompassing so-called BIM-Snippets to encapsulate schematized arbitrary data, yet the BCF is still mostly been used to address human-readable issue management in AEC and examples of implementing BIM-Snippets are not yet commonly introduced. Example of a BIM-snippet could be a partial IFC file.

MINIMIZED COMMUNICATION PROTOCOL

To implement the adaptive detailing of partially incomplete and vague design models in early design stages, this paper uses an adaptive minimized machine-readable BIM-based protocol for communication between the architect and various specialist planners (domain experts). The proposed minimized communication protocol used for adaptive detailing is composed of two parts. The first part is responsible for the management and sorting of communication interactions between different actors. It implies a standard ticketing system (also known as issue tracking system). Each request for analysis generates a ticket. In simple words, each ticket will contain information on what type of analysis was requested, by whom it was requested, who's responsible for it, what is its current status and so on. Some common features in this ticketing system are as follows:

- Register a request for analysis (or a ticket)
- Assign an owner, or person responsible, to the ticket
- Assign additional interested parties to the ticket
- Track changes to the ticket
- Inform interested parties of these changes
- Launch activity based on ticket status or priority
- Report on the status of one or more ticket(s) - an overview
- Finish with, or close, the ticket once the activity is concluded.

The second part of this communication protocol contains the feedback provided by various consultants and domain experts. Furthermore, the issues and messages traded between different actors using this protocol are designed to be machine-readable through predefined schemas. Human-readable communication could be comments (free-form text) and snapshots (with free-form annotations), while machine-readable communication is based on predefined and agreed upon schemas, which enables the computer to read, filter and analyse the trafficked messages afterwards. Using this protocol, all communications, variant evaluations, and decision-making will be documented and traceable afterwards for further use cases. Considering the fragmented nature of AEC industry with many small and medium-size companies whose collaborations are mostly limited to the duration of one project, we believe that through machine-readable communica-

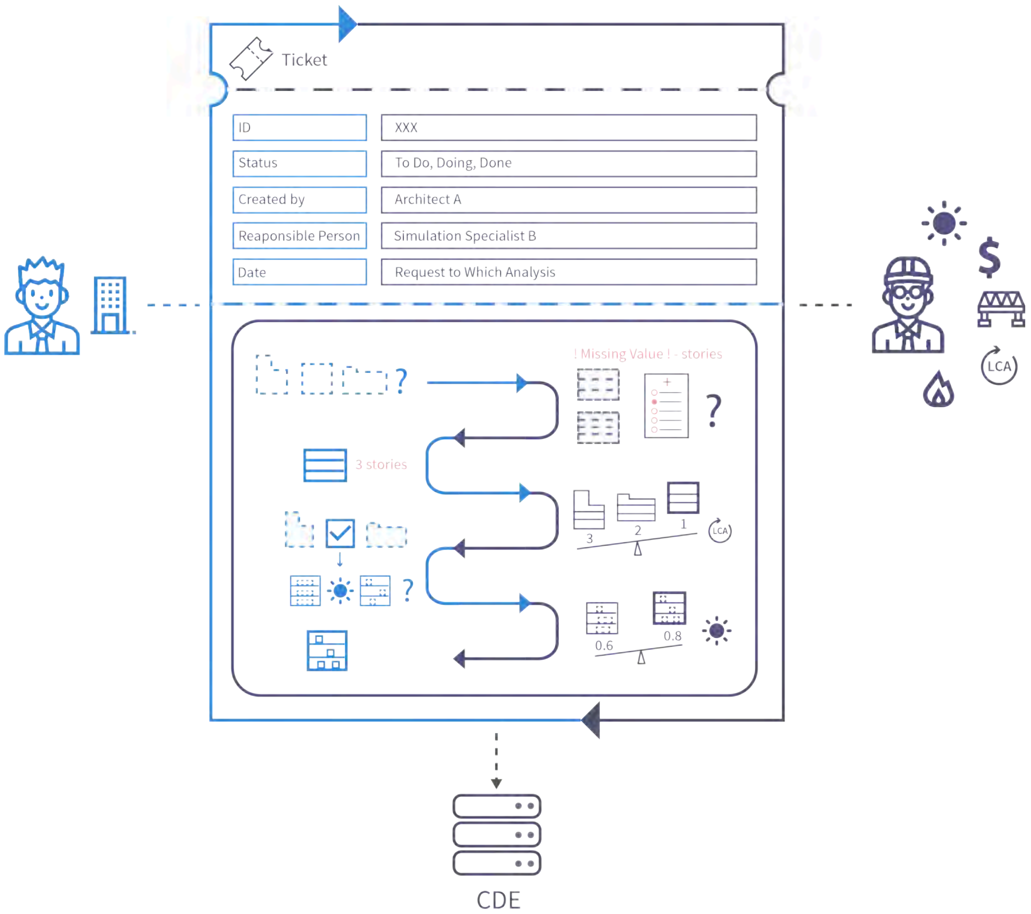

Figure 1
Outline of the Minimized Communication Protocol

tions, we'll be able to learn from the partnerships and interactions of various building projects and that might help to improve this less advanced industry.

Based on the explicit exchange requirements needed for each analysis (examples in our research group are the energy & structural analysis) a specific schema is defined for each analysis (using the requirements planning via Multi-LOD Meta Model (Abualdenien and Borrmann 2019)) that contains all the essential components (spatial and semantical building components) with their corresponding crucial attributes and LOD (Level of Development) within the BIM data model. This part uses an adaptive signature function called 'Feedback' to exchange the missing information along with suggested values for them as options. This signature function based on its use case will receive different arguments. The feedback function in its general form is as follows:

```
feedback (actionType, optionGroupID,
 ↪ GUID, aLODx, ComponentID,
 ↪ PropertyID, value)
```

Each of the arguments that the feedback function receives along with two demonstrative examples for energy analysis and structural analysis has been explained in the following publications (Zahedi et al. 2019; Zahedi and Petzold 2019).

IDENTIFICATION AND INTERACTIVE EXPLORATION

During the early design phases, the building models are characterized mostly by containing incomplete or vague information. In order to obtain meaningful simulation results, a partial detailing of the information content according to the requirements of the simulations might be necessary. The aim is that the domain-experts (responsible for various analysis and simulation methods) can request additional information in design models if they are not sufficiently detailed. The information deficits identified in this way must be indicated to the designer (architect) in an appropriate manner so that he can make the necessary detailing decisions.

Moreover, communication and visualization go hand in hand in order to ensure good collaboration between different actors to evaluate the developed design variants. Visualization is an essential part of communication and exploration. Throughout this adaptive detailing, visualization consists of two major domains. One being the modifications and reporting of missing details in BIM models, and the other one is the representation of different analysis and simulation results along with the illustration of assessments and evaluations of respected design variants. The first category mainly consists of illustration and manipulation techniques concerning BIM models content on both spatial and semantical levels. The steps and tasks for visualization design in this domain could be categorized as:

- Missing details report
- Modifications report for the suggested options
- Interactive search with suitable filter techniques
- overview maps and 3D annotation techniques
- manipulation of building components
- dialogue and chat history related to each analysis call

Considering the visualization as an essential part of communication and exploration, in order to ensure good collaboration between different actors, various visualization techniques are suggested in order to properly show the outcome of the model checking to the architect indicating the shortcomings of his design model. For visual identification and exploration of missing information or modified model elements, methods such as overview maps, colour coding and 3D annotations, 2D/3D navigation techniques, walkthrough, exploded views, semantic zooms are proposed. Some of these methods are shown in Figure 2. Currently, in user studies, evaluations are carried out using mock-ups that will lead to a better understanding of the architects' (as the possible users of this system) needs and preferences.

CONCEPTS FOR THE REPRESENTATION OF RESULTS

In order to assist and support the architect in his design decisions, different domain-experts and consultants are asked to provide him with analysis and simulations regarding the future performance of his possible design variants. Using analysis results as objective criteria for the assessment of design variants necessitates adequate representation and visualization of these results. The architect (not being an expert in every respected field of analysis) desires an easy-to-understand visualization of all these results. When designing visualizations, many different aspects need to be considered. The quality of the visualization could be assessed via its effectiveness,

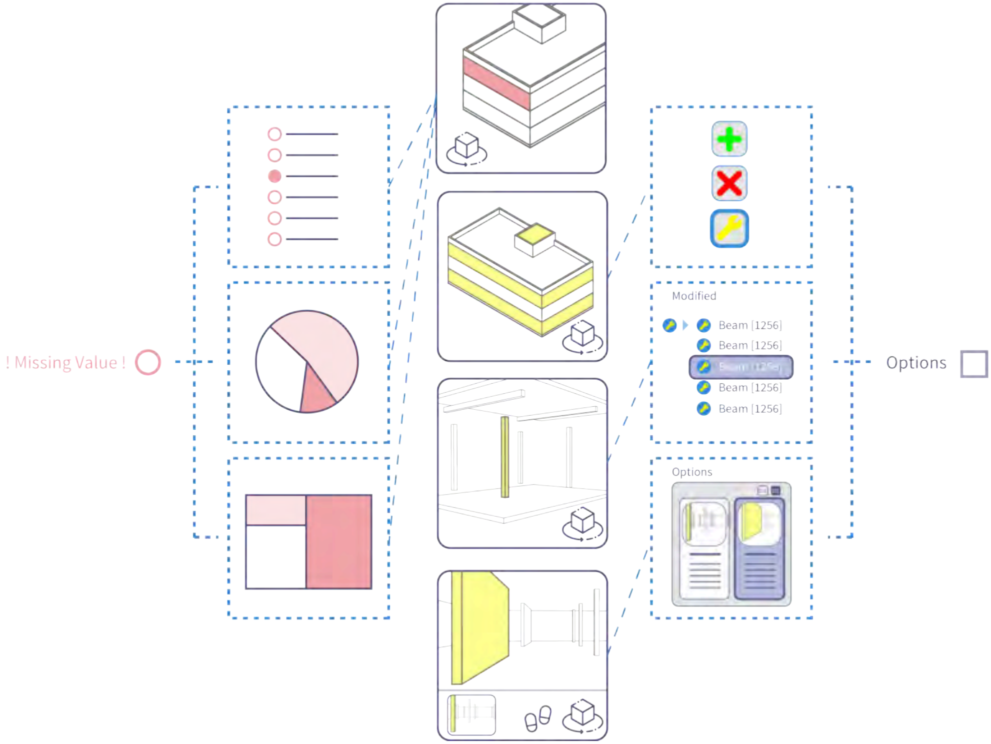

Figure 2
Different
Interaction
Methods to deal
with the Feedback
report

expressivity and appropriateness (Mackinlay 1986; Schumann and Müller 2013). The visualization problem is essentially characterized by questions of what is visualized, why and under what conditions. The answers to these questions represent the object, goal and context of the visualization, respectively. The object of the visualization is determined by the underlying data and the goal by the task that the user wants to solve. Characteristics of the user such as his cognitive abilities, experiences and preferences are also influencing in defining the visualization problem. Context represents the background of the application such as established techniques and tools, conventions and metaphors.

In the first step, the object of the visualization is investigated, which is determined by the underlying data of the simulation results. The examples in our research group are the energy and structural analysis. Following with the user whom in our case is the architect. The architect's ultimate goal is to evaluate and compare design variants using analysis results. The context in our case is the building design which is represented by the Building Development Level (BDL). BDL describes the maturity of the overall building model and its refinements in five levels. In the scope of early design stages, we consider BDL 2 and sometimes BDL 3 suitable for these stages. More details about the BDL concept could be found in (Abualdenien and Borrmann 2019).

In general terms, one of the essential possibilities for user support in visualization is the assistance in visualization design. Assistance methods and procedures can differ based on their targeted aspect of visualization design. In particular, considering the procedure, a distinction can be made between constructive (bottom-up) methods and template-based (top-down) methods (Lange et al. 2006). Most constructive methods are based on a rule-based approach. A prototypical example is being implemented for the 'Visualization Support For Assessment And Comparison Of Building Design Variants' based on constructive (bottom-up) approach. Figure 3 shows the conceptual framework of this prototype while Figure 4 and 5 show the screenshots of the InProgress implementations.

EASY-TO-UNDERSTAND EVALUATION OF DESIGN VARIANTS

The design and realization of a building start in the first place with requirements planning. This includes the exact determination of the client(owner)'s needs and demands. His demands and wishes are noted in both qualitative and quantitative forms in the so-called user requirements program. Starting with the design process, the architect creates multiple design variants overviewing different solutions. The client's requirements will later be used to evaluate and compare these design variants. Favourable and selected design variants are detailed further. As mentioned before the key to improve decision-making during the important early design stages is to involve and corporate with domain-experts regarding different design decisions. As part of a master thesis done by

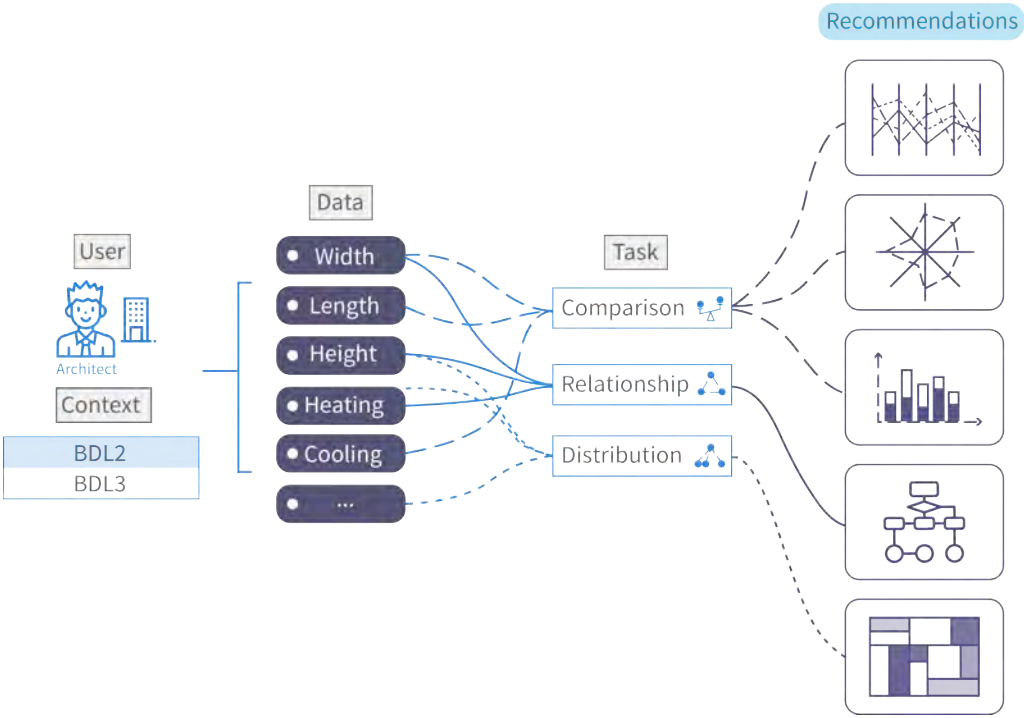

Figure 3
Support in the selection of visualizations

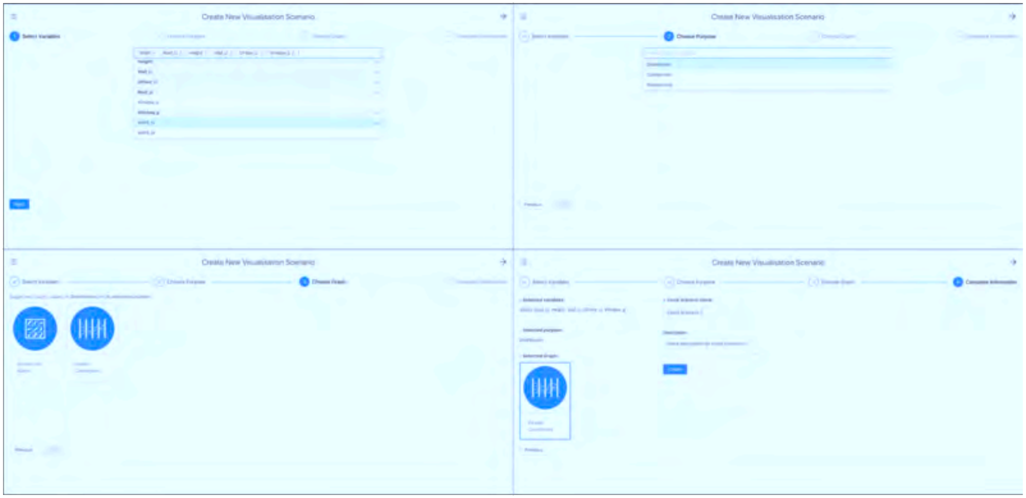

Figure 4
Storyboard screenshots of creating a new visualization scenario

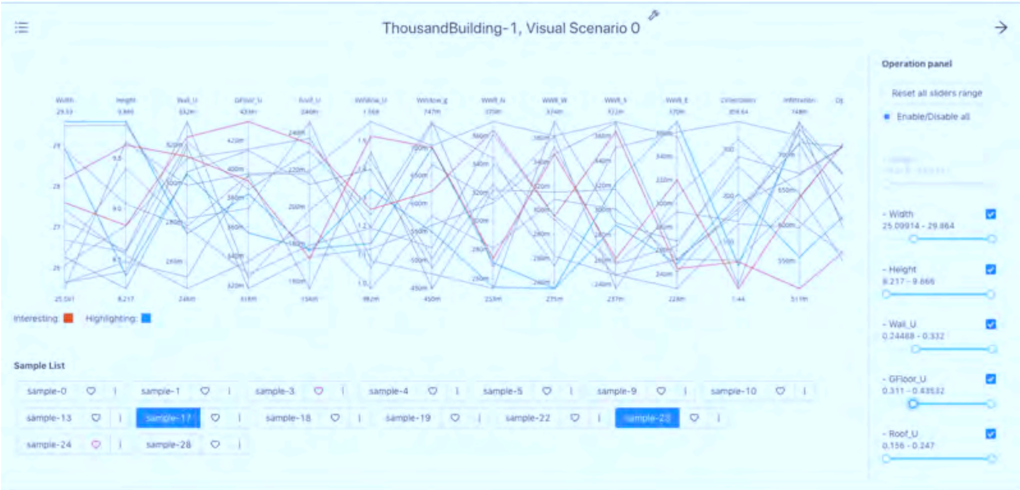

Figure 5
Screenshot of a visualization scenario in our prototype

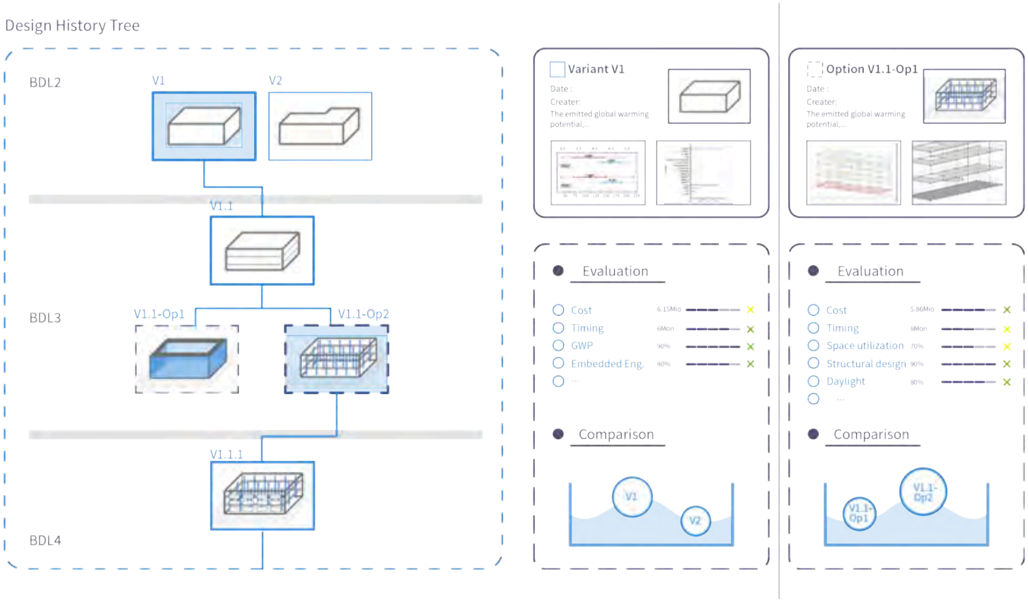

Figure 6
Design History Tree with Variant-Cards and Variant Comparison using KPIs

Carolin Wolff (Carolin Wolff 2018), a total of 15 experts in the AEC industry, including university professors and industry professionals were interviewed in order to find a framework to facilitate collaboration between the architect and the domain-experts during the early design stages.

Among the users' wishes, stated by interviewees, was to include the history of design in the form of a tree or graph including all variants (created by the architect) and options (suggested by the domain-expert to fulfil information deficits in design model) together with so called variant-cards (Carolin Wolff 2018). The function of a variant-card is to recap and review all the essential info related to each design variant into a card. Each variant-card include a thumbnail of the 3D design model and a short description to recap the variant's properties. The important information associated with each variant plus the results of various analysis and simulations are included in the variant-card. This summarized information is linked with more elaborate and comprehensive explanations, which can be called upon if requested. Using these variant-cards the architect can summarize and sort out his design variants.

The design history tree contains all design variants and options throughout the design process and across different BDLs. It is worth mentioning that this paper distinguishes between design variants and options. Options are partial design models suggested by domain-expert to fulfil the information deficits required for analysis compatibility, whereas design variants are directly created by the architect. The architect as the design team leader can choose from design options to fulfil his needs or reject them. Furthermore, decision points where the architect has made his choice regarding design decisions are visualized on this design history tree. Related evaluations and comparisons on these decision points are likewise visualized. Throughout the design process and while making design decisions, the architect uses various criteria to evaluate and compare his design variants and to make different choices. These criteria may include client's requirements such as cost, time or other functional requests, restrictions and regulations demanded by construction authorities, performance and sustainability of the future building and so on. Each of these factors (criteria) could be seen as a Key Performance Indicator (KPI) for the future building. The KPIs may also include any other subjective indicators that the architect may have in mind. Utilizing the Key Performance Indicators (KPIs) allows the architect to assess and compare different design variants. By means of weighting the KPIs, the architect can set priorities for variant evaluations. Figure 6 suggests a conceptual framework that shows the history of design in the form of a tree. This design history tree also contains the decision points where the architect evaluates and compares his design choices based on adaptable KPIs.

CONCLUSION

Variant evaluation and comparison play a significant role in supporting the decision-making process of the architect during the early stages of building design. This paper discussed the use of a minimized computer-readable communication protocol based on BIM to interact with domain-experts (representing various analysis and simulations). Furthermore, the article explained different methods for visual representation, identification and exploration of feedback reports based on the earlier mentioned protocol. Additionally, a prototypical implementation to support the selection of visualization methods for the representation of simulation results was described. Finally, a framework was designed to enable easy-to-understand evaluation and comparison of design variants.

ACKNOWLEDGEMENTS

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BIM-Aided Prefabrication for Minimum Waste DIY Timber Houses

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The continuous housing shortage demands efficient ways of design and construction. In the context of rising construction standards and shrinking manpower, one of the possible answers to the problem is prefabrication oriented towards do-it-yourself (DIY) construction methods, which could contribute to the low and middle income housing supply in the market. The article covers the process of developing an experimental tool for aiding single-family housing design with the use of small-element solid timber prefabrication, suitable for DIY assembly. The presented tool uses the potential of BIM technology adapting a traditionally-designed house to the needs of prefabrication and optimizing it in terms of waste generated in the assembly process. The presented experiment was realized in the Autodesk Revit environment and incorporates custom generative scripts developed in Dynamo-for-Revit. The prototype analyzed an input model and converted it into a prefabricated alternative based on the user- and technology-specified boundary conditions. The prototype was tested on the example design of a two-story single-family house. The results compare the automated optimized model conversion with manual adaptation approach. The implemented algorithm allowed for reducing the construction waste by more than 50%.

Keywords: *do-it-yourself construction, do-it-yourself house, generative BIM, BIM-aided prefabrication, small-panel timber prefabrication, self-help housing*

INTRODUCTION

Prefabrication is nowadays a standard in housing construction in many countries worldwide. It is considered faster, safer, cleaner and, due to the benefits of mass production, also cheaper. Contemporary prefabrication features a wide range of technologies, varying in terms of prefabricated element size, function and material. Furthermore, the mass customization paradigm significantly increased the variety of possible design outcomes. That, along with the development of CAAD and - more recently - BIM opened a whole new world of opportunity before architects.

From the historical perspective prefabrication was usually associated with modularity. A prefabricated building was constructed with limited number of components significantly decreasing the variety of possible outcomes. This kind of highly repetitive typicized architecture is characteristic for mid-20th century low quality concrete large panel systems, popular especially in Central and Eastern Europe. According to Tatjana Schneider and Jeremy Till in most cases this kind of prefabrication proved to be ineffective in terms of building flexibility. Simultaneously, flexibility is commonly referred to as a determinant of a well-designed housing. A house or apartment should be adaptable to users' needs changing over time. Most of the known prefabricated housing fail to meet this requirement (Schneider and Till, 2007).

The analysis of existing examples of prefabricated housing raises important questions about possibilities of increasing its flexibility. The overview of past as well as currently available prefabrication technologies reveals a general pattern: the degree of flexibility increases in proportion to manual workability of used material and in inverse proportion to the size of prefabricated elements. At the same time, it is noticeable that contemporary prefabrication trends towards large ready-made modular volumetric units. Volumetric prefabrication offers significant reduction of construction time. The prefabricated modules are practically ready to be used right after the assembly on site. On the other hand, this kind of prefabrication is highly ineffective in terms of transportation cost as well as flexibility.

As pointed out by Nikos Salingaros and Débora Tejada an alternative to modular design is creating a structure through subdivision of the architectural form. This approach allows the structural components to take any dimensions and shape, freeing the architecture and its future users from the limitations of a rigid modular design (Salingaros and Tejada, 2001).

Salingaros' approach converges with the philosophy of Walter Segal - one of the distinguished architects of the 20th century. Segal is known for his self-build method in which adaptability can be achieved with the prefabrication with simple materials such as timber. Segal's method assumes using standardized yet flexible elements rather than inventing a new standardized system. Additionally, his approach enables users to build homes on their own (McKean, 1989). It extends the meaning of flexibility by introducing the do-it-yourself (DIY) method which not only allows unqualified users to construct their own houses but also to alter them according to their needs changing over time. Furthermore, the term 'flexibility' can be applied to the material itself, as timber can be processed both by machine and manually on-site in order to achieve the desired outcome.

These observations encouraged me to explore possibilities of applying a small-panel solid timber prefabrication to achieving flexible and easy to build houses. Along with the flexibility, timber is also a sustainable material, which is a significant factor in terms of developing universal solutions. At the same time, small panels are easier and cheaper to transport and offer a good structural performance.

RESEARCH BACKGROUND

Problem Statement

This paper covers a prototype solution for adapting a single-family house design to the purpose of a DIY-oriented timber prefabrication. The objective was to make a small-element solid timber prefabrication (Fig. 1) a relevant alternative to traditional construction technologies as well as other prefabrication techniques. At the same time, the presented solution aims at preserving the architectural diversity by applying the mass customization paradigm. To address this issue, I proposed an algorithmic BIM-based tool which enables automatic generation of geometry of prefabricated timber panels based on the input model. The goal was to maximize benefits of mass production by generating as many repeatable elements as possible.

The main advantage of using a solid timber structure is that the non-repeatable elements can be achieved either with off-site CNC fabrication techniques or by manual on-site adjustments. The minor manual adjustments can be performed by unqualified user, which significantly increases the building's flexibility potential. Additionally, due to the solid timber structure there are no limits in terms of interior arrangement, in terms of casework for example, which further increases the flexibility. Due to simple carpentry joints between panels the partition walls can be demounted and placed elsewhere according to the user needs. At the same time, timber is a carbon-negative material and, due to moisture diffusion, it provides a good living microclimate.

Figure 1
The example of a small-element solid timber structure. Courtesy of Artur Stępniak/Svobo.pl.

The main requirement for a DIY approach is choosing the size of prefabricated elements so that they can be handled manually by 2-3 people. That indicates the maximum weight of a single element. The weight value can be specified based on the local labor law or user's individual preferences. The element's weight impacts its dimensions which are then calculated automatically based on the data obtained from the BIM model.

Simultaneously, timber construction, similarly to other building technologies, generates waste in the process in the form of unusable cut-off fragments. The aim of this study was to simulate the prefabricated structure and to optimize the panelization in terms of generated waste.

Related Work

In the recent years fabrication techniques in the building industry have witnessed a major advancement. A modern approach to prefabrication answers the needs for architectural diversity. Technology and methods of contemporary prefabrication were addressed in a book *Robotic industrialization: automation and robotic technologies for customized component, module, and building prefabrication* by Thomas Bock and Thomas Linner (2015). In this publication they present industrial solutions for both typical and custom developments, designed with most commonly used materials, such as brick, concrete, wood and steel. They also address the design specificity, flexibility and sustainability of prefabrication with each material.

Simultaneously, the problem of DIY approach to housing is not widely addressed in recent research in the field of housing. There are few publications undertaking this theme. Among these it is worth to mention the *Self-Help Housing* by Peter Ward (2019) who analyzes this issue from historical and social perspective. He highlights that the DIY and self-help construction approach was a result of the private and public sectors' inability to meet the housing demand.

In the context of CAAD and computational design the problem of DIY houses was undertaken by Chung Man Cho and Wei Mu (2013) who proposed a glued bamboo (glue-bam) prefabricated construction system integrating computational design application with material to achieve DIY housing.

The issue of BIM-aided prefabrication was undertaken, among others, by Mohammed Mekawy and Frank Petzold affiliated with Technical University of Munich. Mekawy's research focused on concrete prefabrication in large scales: volumetric modules (Mekawy and Petzold, 2017) and large panels (Mekawy and Petzold, 2018). Whereas the first paper presents an exhaustive method of generating all possible solutions, the latter work presents an automated rule-based system for early design phase evaluation. Similar approach can be found in the "SeeBIM" prototype (Belsky, Sacks and Brilakis, 2016) which identifies topological relationships between concrete design elements.

METHODS

The prototype was developed for the Autodesk Revit environment extended with Dynamo and custom scripts. It operates on a standard BIM model from which it extracts the information about the building structure. The algorithm collects the positions and dimensions of walls, slabs and roofs, as well as openings such as windows and doors, and organizes them hierarchically according to level, category, host (for openings) and type (Fig. 2).

Prefabrication Constraints

In the first phase, the algorithm computes the maximum sizes of prefabricated elements. For walls the maximum panel width is calculated based on the building level height, assumed wall thickness, user-defined maximum weight and average structural wood density. In terms of slabs and roofs the level height is replaced by the slabs' span. In the assembly process the panels are joined with grooves milled on each vertical edge as shown in Fig. 3. The effective panel coverage is therefore reduced by the width of the grooves, that is, approximately 15 mm [1]. Additionally, due to fabrication constraints the panel width should be a multiple of 4 and should not be smaller than 36. In further phases the algorithm uses the calculated values as a boundary conditions for wall and slab panelization. In this paper the panels of maximum allowed width will be further referred to as *standard panels*.

The small-panel timber prefabrication requires introducing additional constraints. In order to assure a proper structural stiffness each wall needs a foundation and cap beam of 100x100 mm profile, which decreases the height of a standard panel by 200 mm. For the same reason, each windowsill needs to be capped by a similar beam. Furthermore, like in traditional construction, both windows and doors require a head beam which spans over panels directly neighboring the opening (Ostrowska-Wawryniuk and Stępniak, 2018). The typical subdivision of a wall is shown in Fig. 4.

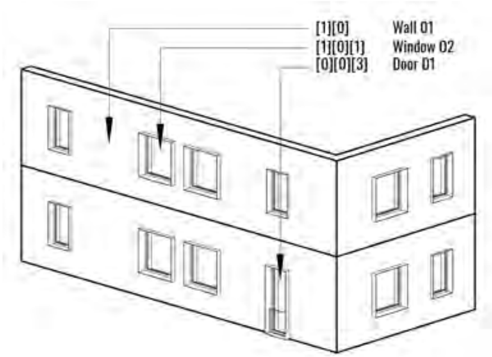

Figure 2
Hierarchy of model elements (Ostrowska-Wawryniuk and Nazar, 2018).

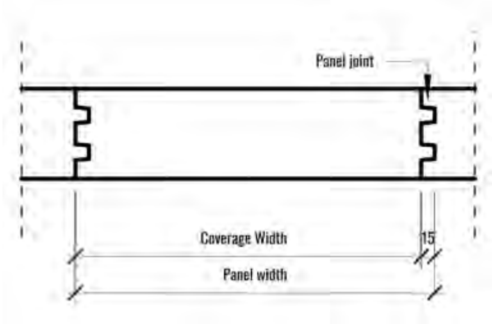

Figure 3
A schematic horizontal section of joint panels.

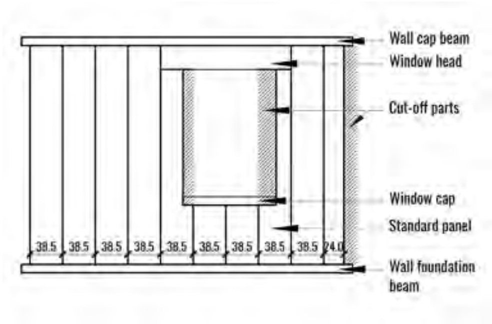

Figure 4
A schematic subdivision of a small-panel solid timber prefab wall.

Splitting and Panelization

In the second phase the algorithm examines the model in order to obtain its geometric structure. The walls are simplified to their location lines (centerlines). External wall location lines are then combined into polygons and partitions into open polylines. The openings are then projected onto location lines indicating the span of each opening in its host wall. The obtained data is organized according to the hierarchy of data in the base model.

Afterwards the splitting routine generates a preliminary *division scheme* containing a collection of split points on the wall polygons and polylines. The location of split points fits the aforementioned prefabrication constraints. Due to prefabrication constraints the division might result in a number of non-standard panels. In the next phase the division scheme can be further optimized in order to minimize fabrication cost and construction waste.

The division scheme is then appended with the pattern of wall foundations and caps, as well as opening caps and heads.

Optimization

In buildings that are not designed with modularity in mind it is almost impossible to achieve a perfect repeatable panelization. In most cases the resulting structure features several non-repeatable elements which usually appear in walls' endings. These custom panels can be fabricated off-site. However, the advantage of applying timber panel prefabrication has also the potential of achieving non-standard elements by manual on-site adjustment of the standard ones.

In case of small number of non-standard panels, the manual manipulation is cheaper than off-site CNC fabrication. Therefore, apart from automating the panelization process the goal was to minimize the waste generated in the process.

In the proposed solution the panelization is generated in such a way that the maximum possible number of non-standard elements can be combined into larger standard panels. In other words, in the proposed solution the leftovers, such as cut-offs appearing at wall endings, can be reused elsewhere in the structure. In order to enhance the optimization, I introduced an additional module parameter, which allows for adjustment of the standard segment width to further minimize the material waste.

The optimization is conducted based on the algorithm which balances the three criteria:

1. The maximum panel width: the algorithm prefers the highest width obtainable with the predefined weight constraint.
2. The minimum waste: the algorithm prefers the panelization where the most leftovers panels can be reused in other parts of the structure.
3. The minimum type count: the algorithm prefers the solutions with the most repeatable panelization.

Geometry Processing and Documentation

The final panelized geometry was achieved by creating parts for each structural component. The parts were then split on the basis of the division scheme. Afterwards each panel is assigned with a unique id number necessary for on-site assembly.

Finally, for each building wall the program generates a shop drawing and detailed schedule for fabrication and assembly.

RESULTS

The prototype was tested on the example two-story single-family house with the area of 80 m2, story height without finishing of 271 cm and external walls perimeter of 32,24 m (Fig. 5). With timber panel structure the wall thickness could be reduced to 10 cm allowing for saving approximately 3,2 m2 of space in comparison to traditional technologies. Since each timber wall required a 10x10 cm foundation and cap beam in order to assure the proper stiffness, therefore, the effective height of a prefabricated wall panel was 251 cm. The analyzed building requires 25,27 m3 of solid wood for all structural components.

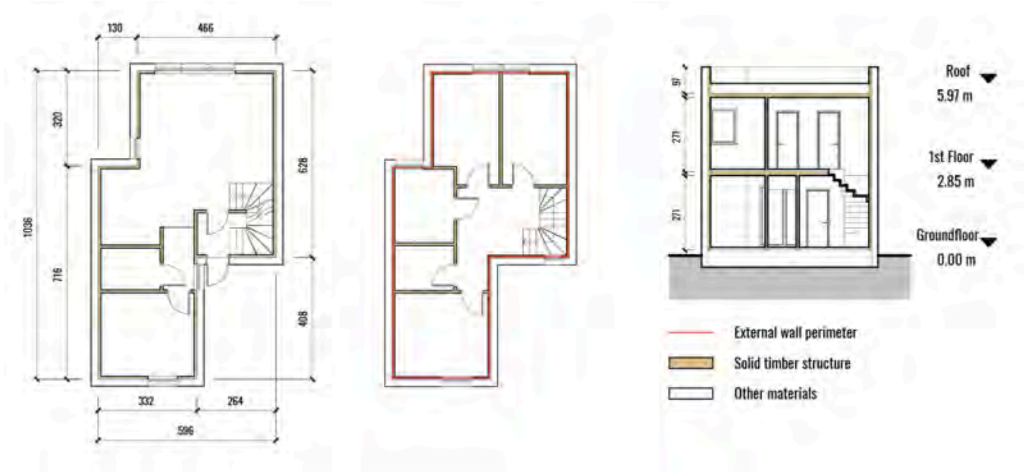

Figure 5
The analyzed building scheme.

For panel size calculation the average wood density was set to 450 kg. In order to enable the assembly to be pursued by two people the maximum panel weight was set to 50 kg. Based on the above constraints the maximum calculated panel width was 44,26 cm. This value was then rounded downwards to 44 cm in order to meet the fabrication requirement of width being multiple of 4. The resultant standard panel measured 44 x 251 x 10 cm.

In manual division process the panelization is determined for each wall separately, starting from an arbitrarily selected end. This kind of approach results in the highest waste rate. For the standard panel division the non-optimal total panel count was 282 (Fig. 6a). The outcome included 146 full standard panels, 14 panels requiring manual or CNC adjustment due to window openings, and 26 panels of non-standard width on wall endings. Only 4 of these irregular panels could be combined into standard-sized elements. Additionally, there were 6 shorter panels under wall openings, which could also be combined into standard panels and 20 shortened panels neighboring door openings. Similarly, 78 shorter panels appear also in the attic level. These panels, however, can be produced in their final size during fabrication. For the standard non-optimized panelization the construction would produce 26 cut-off elements (1,05 m3) of waste which stands for 4,2% of the total timber required for the construction of the analyzed house.

The optimized distribution of standard panel division (Fig. 6b) featured a better adaptation of the cut-off elements. It allowed for reduction of the waste generated by cut-off ends by 0,55 m3 (52 %) although the panel count remained the same. Afterwards the algorithm tested decreasing the standard panel width by 4 cm to 40 cm and then to 36 cm. This process improved the solution by 70 % and 64 % respectively in comparison to the non-optimized outcome (Fig. 6c and 6d).

Surprisingly, the panelization with the standard panel width of 40 cm turned out to be the best in terms of waste minimization. As expected, the narrowest panels provided the closest fit in the base structure, but at the same time, they generated the biggest number of short cut-offs that could not be adapted elsewhere. In the panelization with 40-centimeters panels over 50% of cut-offs were wider than 20 cm and therefore, could be adapted.

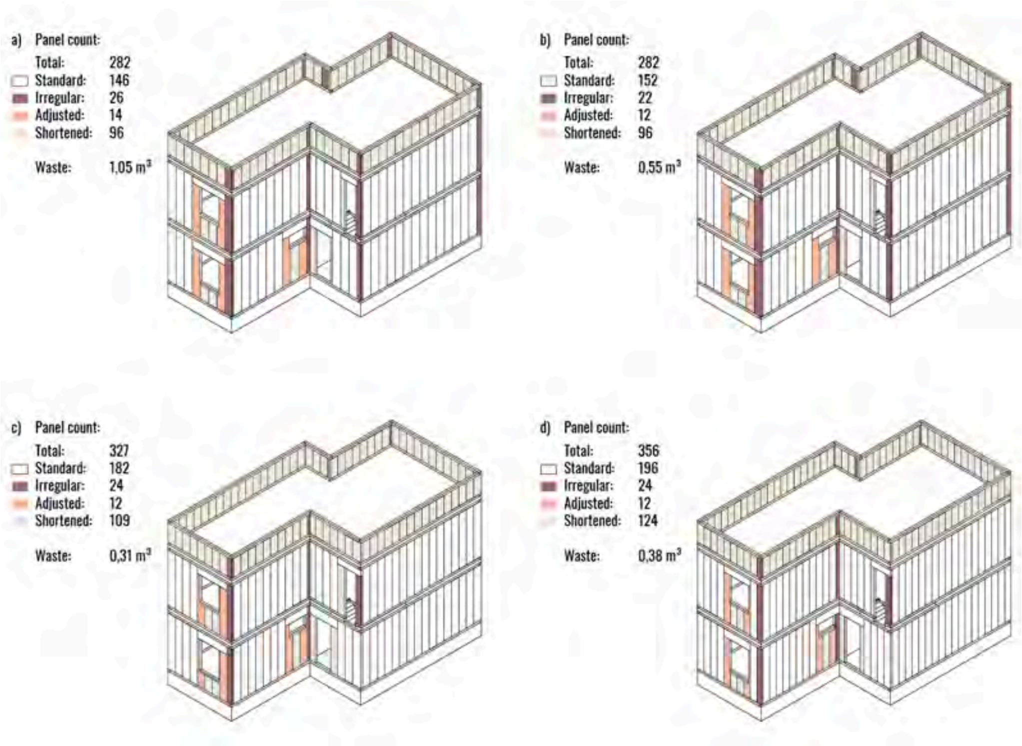

Figure 6
Comparison of achieved panelization results.

DISCUSSION

The aforementioned results show that implementing an automated routine to the panelization phase could contribute to decreasing the amount of waste in the process of the small-element solid timber house assembly. In practice, the subdivision process is often performed manually. As a result, it is pursued when the design phase is concluded. Consequently, due to time limitations, the final solutions are rarely optimal, since adjusting them would require repeating the whole process. Considering that the proposed solution is scalable, I believe that the material efficiency could be even more distinct in larger developments.

By implementing timber structure, I hope to not only increase the building's flexibility, but also enhance its sustainability. In the context of global changes such as global warming and shrinking resources, turning towards renewable and climate-friendly materials is a crucial step in housing development.

The presented BIM-based tool allowed for a real-time simulation of a prefabricated construction. The simulation could be adjusted according to the changes in the building design, which has the potential of improving the decision-making process and design sustainability in early design stages. The original BIM model could be utilized to compare and contrast different options based on multiple criteria.

Finally, the DIY approach responds to the arising demand for bringing the designers closer to their clients. Simultaneously, by limiting the number of qualified workers in the construction process, the solution could significantly decrease the total cost of investment, which addresses the demand for affordable housing. Similar idea was introduced by Cho and Mu (op. cit.). Their idea, however, utilizes glued bamboo (glue-bam) instead of solid timber. This approach converges with Peter Ward's observation that self‐help is a significant driver of low-income housing development, especially in the areas of rapid urbanization.

Although the scope of this paper is limited to small-panel timber prefabrication, the presented prototype is a part of wider research in the field of utilizing BIM environments for design with the use of prefabrication. The prototype will be further developed in order to become a computational aid for participatory design of single-family houses and, furthermore, also multi-family developments realized by housing cooperatives. The aim is to create a multidisciplinary interface bringing together architects' creative freedom, structural and fabrication requirements and the ultimate user's needs.

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BIM Chilean Social Housing Analysis

from the 70´s to 90´s

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This research based on education digs on the ``evolution'' of Chilean social housing between the period from 70's to 90's asking us the ``phylogenic'' relation between ``typos'' of designs that developed several problems in the urban fabric development during 20 years of intricate design just thinking in quantity but not quality in our country.The focus in this research is as the first step understanding the design behind dwellings between this time range, then its process of evolution and transformation by users, and then by BIM understand the virtues and defects of each design and rethink the typologies in a housing life cycle look for the next years.

Keywords: *BIM, Social Housing, Catalogue, Design, Intervention, Strategies*

INTRODUCTION

BIM as a design methodology inside the building life cycle can debug the existent problems not only in the new buildings that we are designing for our cities; it is a new opportunity to improve quality of existing buildings, regenerating our cities from the first cell of living, the housing as the engine of living transformation. From that point of view, the chance to work with existent building block by BIM is undoubtedly an excellent laboratory in which the operation factor in our designs and constructions has been put in the test during years, creating a scenario of possibilities from where we can learn about architecture and its evolution over years of use and transformation.

The time dimension was put in test in a set of 18 different cases at the Metropolitan Area of Santiago - Chile, in where our design teams proposed new solutions based on the family heritage protection plan of refurbishment from the Chilean government. We considered all the information available from study cases, simulated data and the speculative proposed solutions from our teams toward a new integration between housing programme, local-urban relations and the building as the mediator between scales.

RESEARCH QUESTION

-Is it possible to analyse pre-existent social housing by BIM and understanding in this process possible strategies to improve the quality of the study cases?

OBJECTIVES

-To generate a comparative study of Social housing typos between 1970 to 1990 as a primary database of knowledge that allows architectural and structural improvements in its life cycle.
-To create a catalogue of data building information

on Chilean social housing in three scales of intervention.
-To promote BIM and digital fabrication as the way to improve quality in pre-existent no optimised housing blocks versus traditional models of design and intervention.

BIM AS DESIGN TOOL FOR SOCIAL HOUSING RESEARCH

For the objectives of this research, we developed in the architectural design studio 6 at University of Chile a Lab for Multiscale Material Research (MMR) in the built environment. The students organized into research teams were detecting preexistences susceptible to be reconverted in new possibilities, through the inclusion of incremental strategies from the detail to the whole building.

We explored cases from the guidelines of intervention based on strategies of the Chilean Ministry of Housing and Urbanism (MINVU) and its housing refurbishment programme PPPF (Program of Protection of family heritage) integrating 3 scales of application from the whole (common spaces), programmatic enlargement (Housing) and thermal envelope (material detail).

In this direction, we promote the ability to generate simple codes, as project constraints, generating a language from the original structures as the base of multiscale formal systems, studying evolutionary or emergent processes with BIM and Digital Fabrication.

Under this logic (Smal, Medium, Large) the operations to be carried out at the micro level affects the following levels and vice versa, facilitating the feedback within this design process, integrating analogue and digital tools from simple elements like points, Vectors and surfaces, and also simple instructions, whose combination moreover, iteration generate different and “unexpected” results.

REBUILDING BIM FROM EXISTING BUILDINGS

The projects and products of this work are the conceptual base material for MINVU as a collaborative structure between the faculty and this Chilean public organization, delivering all the production by the end of 2019. For that reason, the first step of this work was the detection of iconic social housing typos from the ’70s to ’90s. around the metropolitan area of Santiago.

The starting point was to select 19 cases from areas defined in Santiago as “popular” neighbours that are marked in red from data developed by “Fundación Vivienda” in Chile. In all these areas, it is possible to detect social housing typos that were populated without differentiation from the north to the south of Santiago as well in the whole Chilean territory. (fig 1)

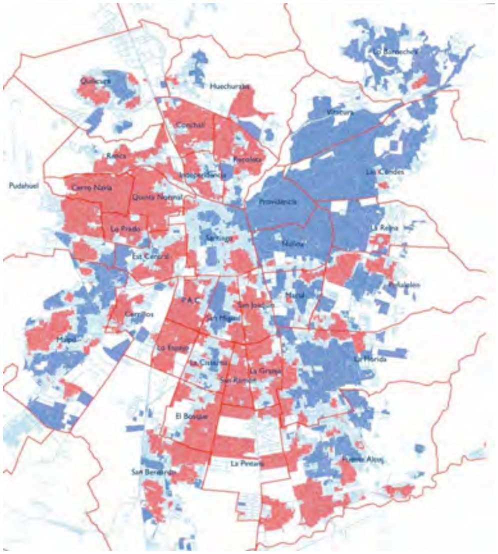


Figure 1
Map of social housing areas in Santiago, source “Fundación Vivienda”

After this field search, the teams selected the following cases: Marta Colvin, Andalucía, El Pinar 2, Los Troncos, El Refugio, El Cobre, San José, Pablo Neruda, Los Quillalles, Villa O’Higgins, San Rafael, Villa Navidad, La Faena, Matta Echaurren, Las Dunas, Alonso de Ercilla, Los Poetas,Alberto Larraguibel and Mi Casa.

Figure 2
Sample from case "Andalucía" about space and regulations, source by the authors

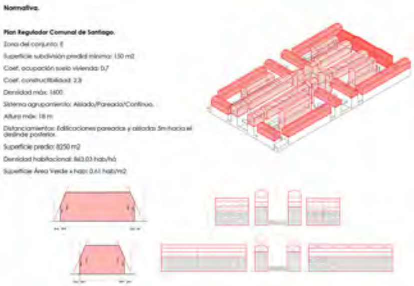


Figure 3
Sample of visual connectivity about space and regulations, source by the authors

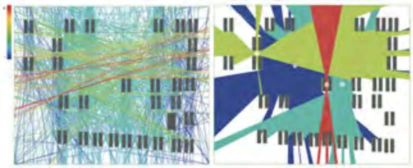
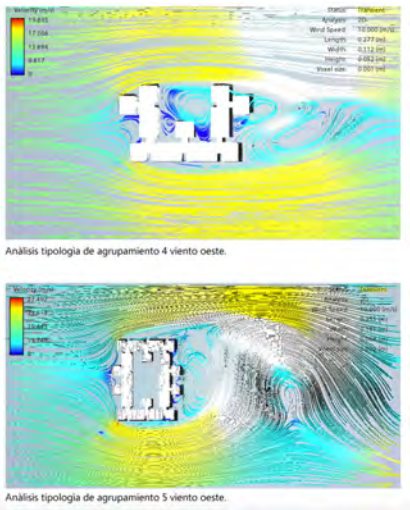


Figure 4
Sample of wind tunnel applied to housing blocks in the case "Alonso de Ercilla", source by the authors



PUBLIC SPACE

The first data collection was all related to public space and regulations over each study case, including the percentage of building versus space on the ground floor. (fig 2)

After the full reconstruction of each case, the design teams modelled graphically in 2d and 3d the restriction volumes from the building regulation of each site. From that analysis, it was possible to define for all the cases the available space now instead of the original existent buildings. All the data collected in this first step generated the base constriction of each new design over the pre-existent social housings, keeping in mind that the first improvement in each study case is the increment of square meters, and over that growth could be possible to re-develop strategies of operation and sustainability.

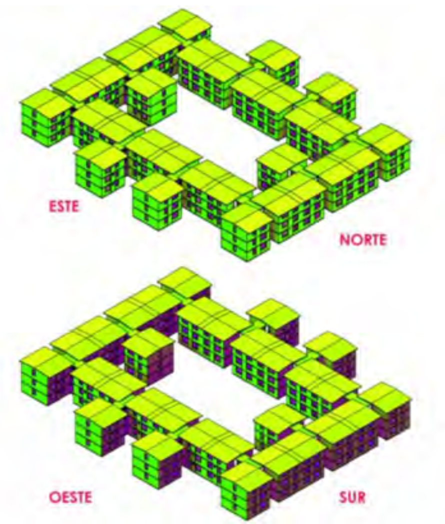
Some discoveries in this step were a comparison in connectivity at public space level as well as relations between public space and radiation and ventilation from wind models over the BIM reconstructions. (fig 3)

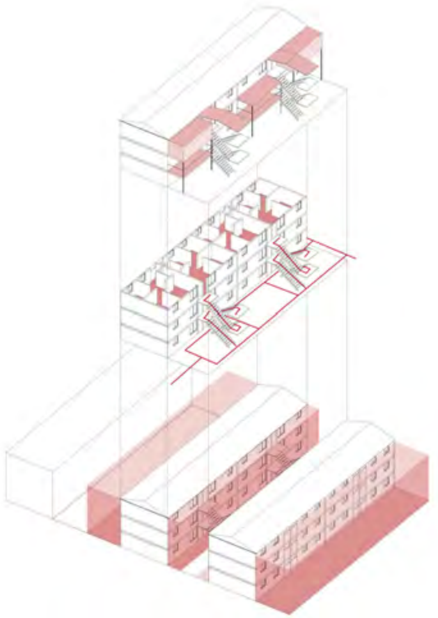
Other approaches over the cases were the relation of original orientations in some cases and turbulences that rejects possible appropriations in public space from the users due to the wind speed, and spiral air movements created areas with extra complexity for regular usage. In other cases, closer distances between housing block developed lack of ventilation (fig 4) as well as projected shadows from one building to public space, creating in this process under radiated areas. (fig 5)

This first stage of studies allowed to develop BIM basic models of each case, running several performance tests over the pre-existent housing blocks, being a highly explorative research scenario that built a dense framework of performative information, that proved to be consistently a co-reading system of the real situation for these unsuccessful living models between the 70s to 90s.

INTERIOR SPACE

This study will bring to the design teams closer to new production processes, from the outside scale to the interior space, from formalities of non-standard architecture to the sense of equity closer to the logic of gene (variation, mutation). This process allowed improvements by variations of the percentage of voids and glassing in facades, increasing square meters of each original floor plan in parallel.





Understanding the possibilities of each case, the analysis in this step was ruled by circulation mapping, interior space capabilities, square meters available in each variation as well as module combinations as air cube from rooms typology (fig 6).

In the same process, all the regulations are visualized inside each existent sample, as well as the predominant materials involved in the cases, creating a database of general aspects from structural to finishing and self-construction possible aspects. This "deconstruction" BIM process allows developing in the proposal stage new strategies of flexible and transferable designs with different levels of details.

With the focus of facilitating the technologic migration, form one study case to another, as well as generating synergy between the different proposals and orders, all the material and performance analysis were run in individual housing units instead of housing blocks, with the KWh value for each unit and an estimative operation value along a full year (fig 7).

In all the studied cases, the teams detected the same patterns as design problems: the original government focus was at the beginning finding solution to housing just in term of quantity, for that reason the use of cheap raw materials overall in facades and exterior walls. That key factor affected the final energetic performance dramatically during a year operation, with almost the double of energy consumption versus an optimized model. Another critical aspect was the lack of space in the interior of each unit, producing a growing phenomenon over the facades, creating dark voids in the interiors of each unit (fig 8).

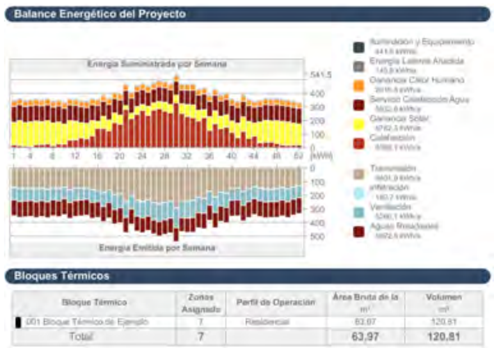


Figure 5
Sample of solar radiation applied to housing blocks in the case "Alonso de Ercilla", source by the authors

Figure 6
Sample of space capabilities from existing transformations, source by the authors

Figure 7
Sample of energy consumption by year from existing housing units from BIM model, source by the authors

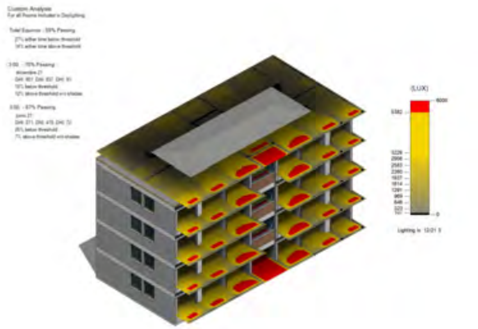


Figure 8
Sample of lux provided in existing housing units from BIM model, source by the authors

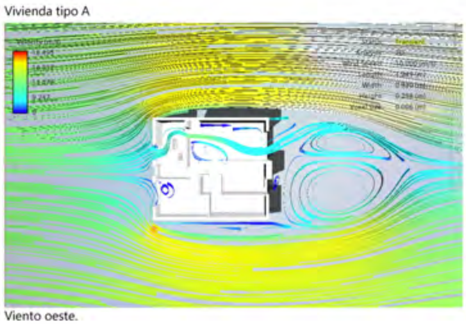


Figure 9
Sample of interior ventilation of a housing sample unit, source by the authors

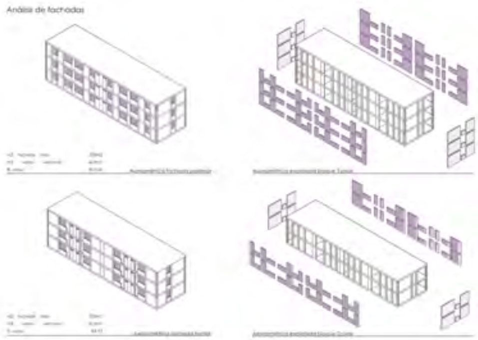


Figure 10
Sample of skin deconstruction in housing block from BIM model, source by the authors

In terms of interior ventilation, the performance of each existent unit was reduced due to the ratio of windows and walls in the facades usually avoid a better result thanks to cheaper solutions designed in the period (fig 9).

EXTERNAL SKIN

In the full process, the design teams emulate conceptual models from the real study cases, towards the construction of visual architectural models with embedded information, allowing modifications at any point in the process for the final transformation step, promoting the incorporation of ideas during the same development. By the recognition of an "external skin" that allows radical refurbishments, this study migrated from rational to experimental simultaneously, democratising the design process and opening the black box inherent in its structures.

The idea behind this stage was the detection of supports that allows transformation and reconnection between public and private space. By definition, the skin is "a thin layer of tissue forming the natural outer covering of the body", understanding this meaning applied to a building like an interface between inside and outside (fig 10).

It was necessary again to run tests of energy consumption, living cost, radiation and illumination for each specific skin, generating a database of information which is the base of all the transformations, creating a catalogue of possible solutions from existent problems (fig 11).

At the end of this process, it was possible to develop a comparison from different models, integrating new designs with old developed structures in a political context that radically changed between the years the 70s to 90s.

Figure 11
Sample of solar radiation in the "external skin" from BIM model, source by the authors

RESULTS

The results of this research are on the one hand a link between technology and design, in an incremental strategy of architecture development in real cases, that are part of a formative model of architectural research based in education, promoting a systematisation in the creative process, from data to real space and vice versa. On the other hand, it creates a critical analysis about what we develop before as country in the social housing field for the studied period and what we need to do over those unsuccessful models of habitable blocks.

After the isolation of half of the cases, we applied to existent blocks an optimised housing models like design restrictions/opportunities by using rules and regulations of the Program of Protection of family heritage (PPPF). As a result of this operation, we generated a new catalogue of projects and strategies.

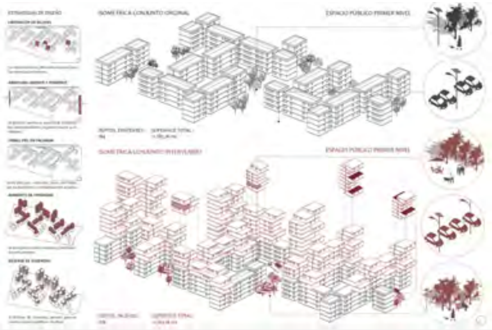


Figure 12
Sample of densification in "Alberto Larraguibel" from BIM model, source by the authors

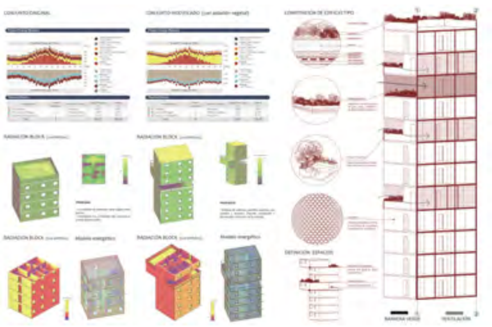


Figure 13
Catalog of transformations over "Alberto Larraguibel", source by the authors

The final stage of this research was based on the second half of the study cases, as BIM densification process by which each case increased its capacity and density in a ratio between 200 to 300 per cent. This new restriction opened the possibility to visualise a possible new design scenario, pushing the base density to a higher level of square meters per inhabitant.In all these three stages, we used the same process: an integration of the whole public space, the house and the building block, and thermal envelope as the mediator between booth scales (the public and the private) in a proposed scale of habitability (fig 12)(fig 13).

NEXT STEPS

For the next steps, the Ministry of Housing and Urbanism wants to develop with us the same process but taking existent models from other Chilean regions. From the north to the south of our country we will develop a new design restriction: different latitudes over the building, creating a new set of results, due to the differences between regions are tremendous in terms of climate, energy and ways to use the space by the users.The catalogue of transformation from each study case will be the base of the phylogenic study that we are developing with all the cases from the year of research running in the Design studio six at the University of Chile. (fig 14) (fig15).

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Figure 14
Full transformation process study case "Marta Colvin" based on the typology from the 90s, source by the authors

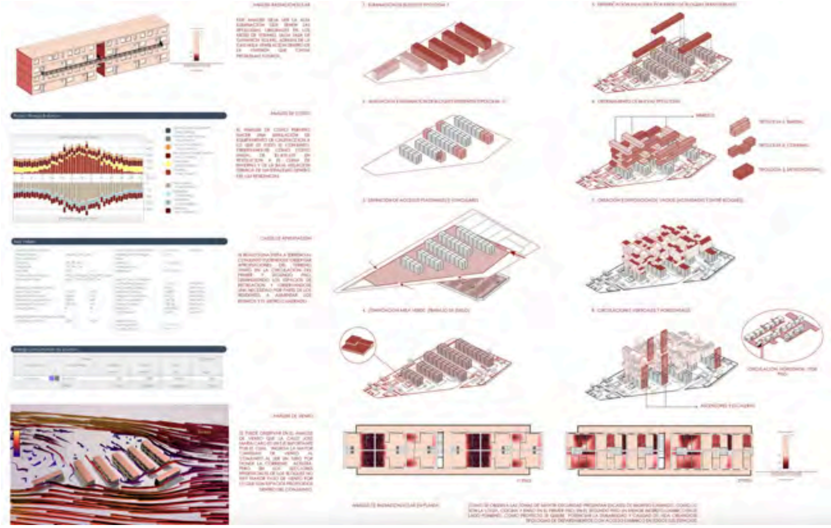
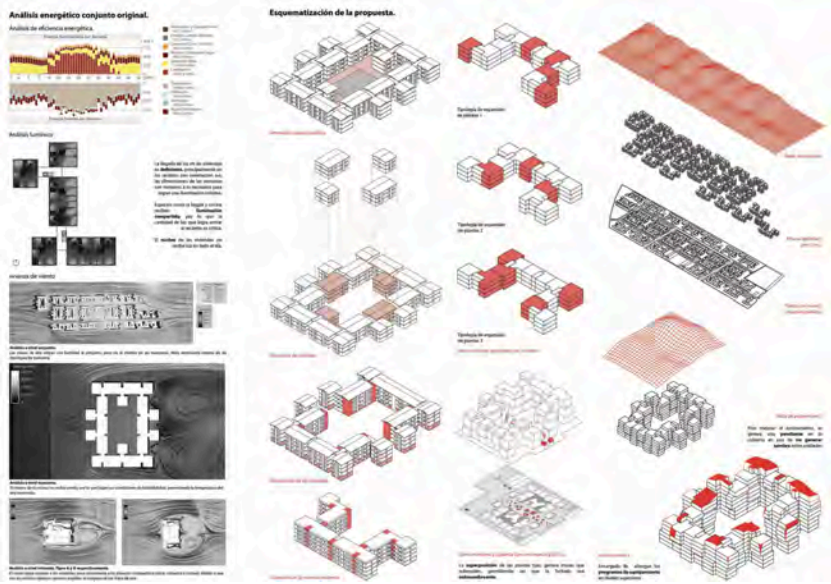


Figure 15
Full transformation process study case "Alonso de Ercilla" based on the typology from the 80s, source by the authors



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Towards Blockchains for architectural design

Consensus mechanisms for collaboration in BIM

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We present a Blockchain collaboration mechanism on optimisation problems between distributed participants who work with building information modelling tools. The blockchain mechanism is capable of executing smart contracts, acting as a reward mechanism of independent designers attempting to collaborate or compete on optimising a design performance problem. Earlier work has described the potential integration through different levels of Computer Aided Design and Blockchain. We present an expanded version of that integration and we showcase how a team can collaboratively and competitively work, using BIM tools, through the blockchain. The original contribution of the paper is the use of the design optimisation performance as a consensus mechanism for block writing in blockchains. To accomplish that we introduce mechanisms for BIM to Blockchain Integration but also describe a special category of blockchains for architectural design and the built environment. The paper concludes with an analysis of the relationship between trust and values as encapsulated in the blockchain and how these could affect the design collaboration.

Keywords: *Blockchain, BIM, agent, collaboration, competition*

INTRODUCTION.

The paper investigates collaboration and competition in architectural design, using a model where agents are competing to create the optimum design for a given design problem, where each optimum found in the design space is used to synchronise all other agents to that solution before the computation begins anew. In the first section of the paper, we discuss issues of collaboration in BIM, trust, versioning, the notion of truth and finally performance in Building Information Modeling. In the next section, we examine the Ethereum (ETH) Blockchain as a generic Turing machine, where smart contracts and transactions change its collective decentralized state. We also discuss previous work we have conducted in CAD-blockchain integration, the concept of Decentralised Autonomous Organisations (DAO) in the blockchain and how they can be used in a design process. We then develop the case for competitive collaboration. In relation to the Ethereum

(ETH)blockchain, we discuss the notion of truth and the mechanism for consensus in the ETH blockchain, and the mechanism with which the Ethereum Virtual Machine (EVM) reaches consensus. We then argue for the application of competitive collaboration in BIM processes through smart contracts running on the EVM. We present the design optimization problem we use as a case study, the Interplanetary filesystem and how our prototype uses the blockchain to reach consensus among competitive and collaborative agents. The paper then ends with a discussion on our findings, limitations, and future work.

COLLABORATION IN BUILDING INFORMATION MODELLING

Building information modelling tools are digital tools that manage a virtual representation of a physical facility, from inception to operations. They are used by the full gamut of the AEC industry and are at the moment the prevalent mode of collaboration. One characteristic that BIM tools frequently rely on is that of trusted collaboration, as every agent in the AEC team, from the client to the architect to the consulting engineers has access to the central BIM model. However, BIM has not solved issues of trust, reliability, transparency completely. According to Brazier, Guerrero] claims of a single authoritative version of a BIM database in a project go only as far as the trust that stakeholders have in the keeper/owner of the database and the infrastructure that the database runs on. This also raises transparency and ownership issues with 'cloud' computing providers and the ownership and control of the BIM files, along with issues of version control and regression in distributed teams.

Ma et al. have found that in architectural design projects that use an integrated project delivery collaborative tasks, such as planning, work creation and execution can be automated via collaborative digital platforms. Chen et al have proposed a system for BIM collaboration via the internet, both via server client and peer to peer collaboration. Within that system, a number of teams are working in parallel in their own BIM silo, with information coordinated amongst the models in key moments in time. Kim et al have also identified time as a critical component of making decisions in BIM supported systems within the masterplanning discipline, where time-dependent metrics and multiple variants can inform the masterplan in a fragmented manner, constraining and making decision making difficult. To counter this Kim et al develop a centralized decision support system for masterplanning that collected all needed digital information into one platform that also incorporated the needed reasoning capacity for decisions. Ma et al(2), further have developed a web-based system, for construction quality inspection that also integrates BIM and a wi-fi based positioning system. One of the features highlighted in this system by stakeholders is the preservation of data in QA processes, following strict protocols, and a record of responsibilities of stakeholders that the system provides. Fittingly Hattab et al analyse information and measure data flows in BIM processes using agent-based modelling and social network analysis. Within their study, they identify fundamental conditions to be met for BIM collaboration to be successful, one of which is setting up BIM as a design "process" rather than a design "tool", where bottlenecks in the collaboration can be identified.

Value then is not only added by identifying bottlenecks but is also added in BIM design collaboration By identifying with the pattern of adding value, the member of the design team responsible, the time this takes place along with the part of the project where this takes place. In a similar study, Hattabe et al (2) identify the pattern of error creation along with the potential benefits of lean management practice in BIM processes, which are the reduction of errors and constraining their diffusion in the team.

Diraby et al have used IFC classes as a vehicle for connecting a BIM model with an energy analysis system demonstrating the analytical benefits of expanding BIMs representational capacity with performance analytics. The same objective has also been accomplished by Jabi et al, but in a much more elegant and succinct representational manner, by using non-manifold topology within a BIM system. Value proposition of tool interoperability in BIM is more widely examined by Grilo et al, where they conclude that value creation is not just tool specific in BIM but includes culture, context, values and business practices. Grilo et al also conclude that contractual issues in BIM interoperability and all the aforementioned issues are only partly addressed by current BIM practices, and only in homogeneous BIM environments.

Brazier et al have examined trust in distributed agent-based design problems, and have framed the difficulty of assigning trust in a design agent automatically. They have also detailed the extend of the problem before trust can be used explicitly in an agent-based design environment. Williams et al have examined behavior modeling and its impact on human to human interactions in collaborations, via the accumulation of data and its subsequent analysis. Guerriero et al have concluded that there exists an issue for trust within AEC virtual teams, where a higher effort and reflexivity is needed by team members to trust data that gets entered by others in the BIM system. Trust and the connection of trust with performance is also an issue which has been investigated by Brazzier in distributed design, as agents in a distributed design environment need to know which action to take in response to stimuli from other agents. Team Reflexivity, trust and collective decision making has also been analysed by Dounas et Lombardi where the distributed nature of a shape grammar and the existence of a decentralized autonomous organization operating on the Ethereum Blockchain is used to allow a distributed team to make design decisions.

From all these we conclude that BIM collaborations would benefit from a mechanism that would allow for data flows to be recorded, responsibility to be assigned to all stakeholders according to actions, data entry is to be trusted for each stakeholder, transparent tool interoperability is desired, digital information is orchestrated from diverse fragmented sources with enough trust, and the orchestration of protocols can be recorded in a trusted manner.

BLOCKCHAIN: BACKGROUND AND PRIOR WORK

Distributed ledger technologies and specifically Blockchain are essentially distributed databases between various computing nodes. Due to their distributed nature, there exists a difficulty in establishing a common, agreed, version of the truth between nodes, as one could write two different strings for example in two different computing nodes hosting each part of the database. Blockchains use a unique mechanism to establish consensus regarding which operation & transaction on a distributed database network is true and which one is not. Compared with a central database, where one queries the database directly, a Blockchain is distributed in various nodes over the network. The main consensus tools with which nodes establish the truth among them are proof of work and proof of stake. Both of these consensus tools create a new block on the Blockchain, validating one operation. This new block becomes the latest block in the chain, hence the term blockchain. Nodes participating in a blockchain network are either full nodes - those containing a full copy of the blockchain, miners - full nodes that also participate in the mining proof-of-work contest between nodes, or light clients - those that synchronise only part of the blockchain to save resources. We have chosen to implement our solutions on the Ethereum blockchain as it provides the following benefits compared to other blockchains: It behaves as a state machine, i.e. a Turing machine that allows nodes to change its state. Thus it is possible to record a variety of information on the Ethereum Blockchain. It also has the benefit of being programmable through code, either in its native language solidity or even python. Code executed on the Ethereum blockchain is called a 'smart contract' as its immutable nature equates the concept of code execution with Law.

Within the Ethereum blockchain, the consensus establishing algorithm is called Ethash, a variation on the Dagger-Hasimoto algorithm. Ethash is currently a proof-of-work algorithm and has three distinctive characteristics: ASIC-resistance, light client verifiability and full chain storage. ASIC resistance means that one does not need special computing equipment to participate in solving the computational problems that consist of the proof-of-work algorithm. In proof-of-work algorithms participating computers must produce a binary blob called a nonce, which when hashed cryptographicaly must produce a value lower than a pre-specified target threshold. Ethash begins with the preprocessed Header, which is derived from the previous block in the chain, and the current nonce. These are combined using a SHA-3 algorithm [Antonopoulos & Wood 2018] to create an initial 128byte mix. A large dataset, held in memory by all full nodes is generated every 30,000 blocks. Slices from that dataset are selected by each computing node, hashed together and then combined with the 128byte mix to generate the nonce that will be compared with the pre-selected target. The node that achieves this feature first receives a coin which is 'mined' for the purpose, hence the term 'mining cryptocoins'. The winning nonce is included in the block that will be the next block in the chain. The existence of the proof-of-work mechanism as a sufficiently hard but achievable hurdle ensures the continuing participation of mining nodes so that the transactions recorded in the blockchain are verifiable each time.

Initial blockchain systems were created so that digital distributed currencies could become possible. However, blockchains allow the computation of much more than simple additions. The full Ethereum network for example with all participating nodes (mining, full nodes, and light clients) is essentially a fully configured Turing machine. Due to the Ethereum blockchain being equivalent to a Turing machine, it has all features of Turing completeness. The positive aspect of Turing completeness is the fact that one can treat the Ethereum Blockchain as a generic computing infrastructure, capable of emulating other computers. The disadvantage would be that the Ethereum blockchain is also susceptible to the problem of incomputability, i.e not knowing for all classes of problems whether a computation will terminate with a solution or indefinitely loop with no halting mechanism. Subsequently, the Ethereum blockchain has a halting mechanism built in, in the form of computation or transaction fees. Any smart contract or code execution - transaction on the EVM needs to pay a transaction fee to be executed. If the Code causes the EVM to go into an endless loop, code execution stops as soon as the fees paid for that purpose are depleted.

In our previous work, we have discussed how one agent can establish a level of trust through combining a CAD system with smart contracts on a blockchain, and the possible levels of integration between CAD systems and a blockchain [Dounas Lombardi 2018]. We have also analysed how one can form decentralised autonomous organisations by exploiting the use of smart contracts for that purpose, and use the DAOs as a tool for design [Dounas Lombardi 2019]. Although DAOs can be currently used as good models for design governance, they are still far from being suitable for iterative exploration of issues of engineering or design performance. Due to their distributed nature, they are good vehicles for establishing collaboration within large groups, but not efficient vehicles for optimization problems. However, Jabi-Aish have created reference models for BIM, using non-manifold topology, where complex information can be represented and manipulated by a proxy model using non-manifold topology, thus greatly simplifying various issues of trust in geometric representation, transformations, and complex operations of energy analysis and structural optimization.

Design optimization performance as a consensus mechanism in blockchain type distributed ledgers.

We present a BIM to Ethereum prototype that uses design performance as a consensus mechanism to navigate issues of trust, transparency, responsibility and value creation between design agents in a distributed design environment. We have structured the prototype in a manner that allows interoperability between digital tools that can communicate with the blockchain Ethereum.

For the sake of explaining the full functionality of the prototype, we present three design agents that are working each within their own software platform. For example, for design optimization problems the agents are working with Revit/Dynamo, Rhinoceros/-Grasshopper, or Blender/Sverchok, all 3d modeling platforms with visual data flow programming capabilities. The objective is to find optimized values for a particular part of the design, say for example, structural performance. [Figure 1]

As such, in our scenario, all three agents are attempting to solve a Structural design problem that has been deployed as a smart contract at a specific address on the blockchain. The stakeholder who sets the design problem has the following options at hand: update the problem, add or withdraw a monetary balance that will go towards rewards, submit the problem, and approve or reject the solution submitted by one of the agents. All these options are structured within the smart contract on the ETH blockchain. Since saving large amounts of data on the ETH blockchain can be particularly expensive, we need another immutable, decentralised manner in which we distribute files between participants. To do so we use Interplanetary File system, IPFS, a distributed filesystem that distributes storage amongst participants. When the stakeholder sets the problem via the smart contract, she also uploads a model file on the Interplanetary filesystem and associates a cryptographic hash with the problem on the smart contract. [Figure 2]

The Structural design optimization problem the agents are trying to execute is described in the following: The process is based on the Finite Element Analysis of a simple structure adopting Karamba as FEM within the Grasshopper environment.The algorithm creates first an orthogonal grid by equally dividing a surface by a variable number of steps. Lines are then transformed into beams while the nodes of the grid become the points where to positioning the supports. For the purpose of this research we simulate the presence of a high number of designer involved in finding the optimal position of the supports by introducing Galapagos, genetic solver of Grasshopper, A random component is applied to randomize the position of the supports and connected to the solver to generate and analyse multiple solutions. The algorithm workflow then follows the standard path to run a finite element analysis by adding a simple gravity load. Cross section and material have not been specified and left as the default one by the plugin. The value used for the optimization are the displacement in the structure ob tained at the end of the analysis. Each value retrieved at the end of each loop is sent to the BC and stored as a solution provided by a potential designer participating to either a collaborative or a competitive project. [Figure 3]

The same takes place with all files in our prototype as storing information on the blockchain is particularly expensive, hence the best strategy is to only store on the blockchain, hashes of specific files, rather than the file itself, which would be very expensive computationally.

The smart contract parameter structure is simple: It includes an address in the blockchain, for example 0xEBE7e47e89129382D0837F067Ed51D318c891307 that holds the smart contract and the funds. It also includes a struct with the following parameters:

- The id of the problem;

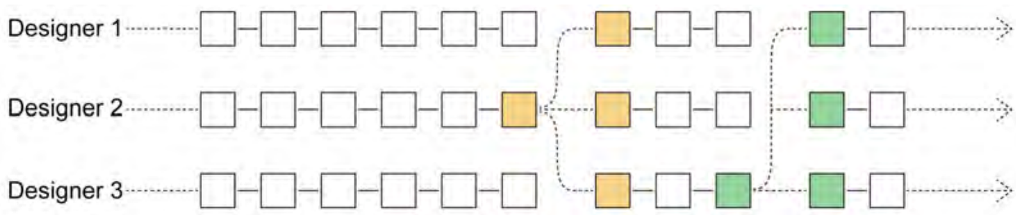

Figure 1
Three agents solving a design problem.

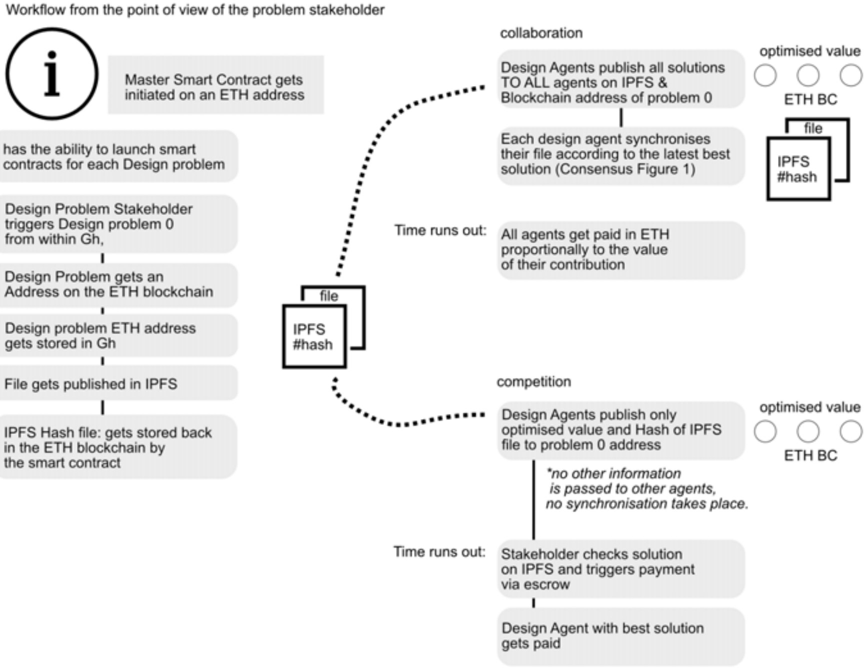

Figure 2
Design problem stakeholder data flow on the Ethereum Blockchain,

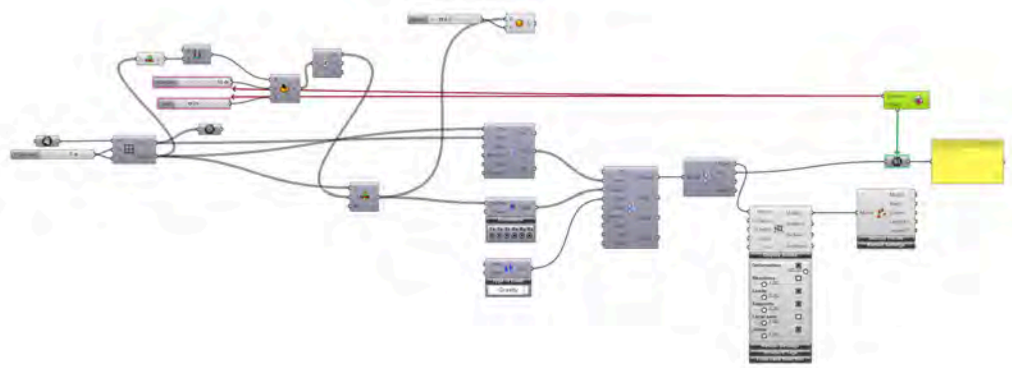

Figure 3
Structural Optimisation in Grasshopper

- The cryptographic hash of the ‘problem’ file on IPFS;
- The desirable inputs/outputs;
- The minimal required performance;
- The reward amount and an expiry date, after which the smart contract stops receiving input for resolution.

On the agent side, the smart contract requires three values to be provided: the user ETH address, a username and a payout ETH address, as one might want to collect monetary rewards in addresses other than the one that identifies the user. When the user goes through solving the optimization problem, a plugin on the BIM platform the agent is using submits to the smart contract the following data: the user address, the problem id, a timestamp that is used to regulate who has submitted first a solution, and a cryptographic hash that corresponds to the file the agent wants to submit as a solution.

In each of the agent’s platforms, the software computes the script and reports to another node which reports to a smart contract on an ‘Ethereum’ blockchain via node.js, a javascript library. The smart contracts compare the value of the node either with the current optimized value and a predetermined threshold, and if the result is better than both, executes a function on the smart contract: the contract asks the agent which has found the higher value to send over her script definition. The definition, once saved in IPFS, is given a hash and is sent over to the other agents which adopt it as the current best performing script. The cycle can potentially continue indefinitely with the smart contract on the blockchain synchronizing all the agents to the best performing script of all.

Within the smart contract one can also execute payment of monetary funds to the node that has found the current optimized value. Thus there is an incentive to the distributed agents to work to find the optimized value and continue to do so. Note that when the node sends the optimization value to the blockchain, if the value is not higher than the current optimum, then the blockchain records the attempt thus creating an immutable log of all design activity. At set moments in time, all agents synchronise with IPFS and their solutions are hashed .i.e. encoded using a SHA256 algorithm, so that even the failed solutions can be recorded and their existence verified and retrieved. The smart contract terminates the problem when time runs out, or when an agent finds the best solution possible.

DISCUSSION

We believe that our work shows promise in solving issues of trust in collaboration with BIM tools and enables new collaborative and competitive modes of practice in architectural design. Our solution is able to record all design attempts, including ones that are “failed”, and all positive steps towards optimisation. It also is able to show who created value when, i.e. who had a creative moment that contributed positively to solving the design problem. Within our implementation we currently show one type of software, however agents could work with different platforms, thus bringing a variety of solutions to the collaboration. This poses thought the interoperability question: when one agent succeeds in improving the required design value, their file is uploaded and saved in IPFS, which then gets transmitted to other agents to use for their own basis. If all other agents are using different software than the winning one, then a translation mechanism is needed to be able to translate a parametric script into another. Mechanisms such as topologic that can encapsulate and describe the logic underlying a BIM model are extremely valuable for this needed translation, but we have not yet tested the interoperability between BIM/visual scripting platforms. Early testing shows however promise. Our solution introduces the dimensions within which Blockchains in architectural design can operate through digital tools.

TRUST, IMMUTABILITY, VALUE CREATION.

Even though Li et al have identified BIM and Blockchain as a low maturity field in blockchain applications in the built environment, our works shows that the possibility to build such tools is valid and real. Low maturity in BIM to blockhain integration, we feel, is due to researchers not engaging with the rich digital tool making potential of modern BIM tools and the Ethereum blockchain, but rather restricting themselves to theoretical investigations. Our processes show how blockchain can be a valuable, workable infrastructure for BIM operations, where trust, immutability and legibility of design responsibilities, and much more importantly value creation, are key for the successful adoption of the technology by architectural designers. The core advantage of using blockchains in architectural design we believe will be manifest when we are able to record on the blockchain continuous loops of optimisations, for example on structure, then on energy performance, then on material optimization, plus any other design action.

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[2] https://github.com/ethereum/wiki/wiki/Ethash

Key for Entering Industry 4.0 in the AEC Sector

BIM Organisation Development

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More and more sectors are entering Industry 4.0 but when we look around in the Architecture, Engineering and Construction industry, we do not see it happening. We wanted to investigate the reason behind this. Therefore, we conducted research among Hungarian design studios to find out what level of development they are at, and what the obstacles could be for implementing the latest technologies. This paper identifies the main problem we uncovered and discusses a possible solution. We explain what BIM Organisation Development is and why it is fundamental for architect studios who would like to enter Industry 4.0. We introduce the so-called Brick+Data Method, specifying its three essential development steps to get BIM technologies implemented and to make architect studios more efficient. Finally, we share our findings according to the feedback of the companies we worked with using this method.

Keywords: *BIM, organisation development, technology implementation, Industry 4.0, design process*

INTRODUCTION

The title of the eCAADe conference this year is "Architecture in the 4th Industrial Revolution". Nowadays, we can barely find an industry that has not already organised a conference about the technological achievements of Industry 4.0 and how it will transform their sector. On the other hand, we can name several promising technologies that have not lived up to expectations. We asked the question: "What is the reason behind this?" When discussing the industrial revolution, should the conversation always be about technology? Moreover, is it even clear to us what these industrial revolutions represent?

WHAT DOES INDUSTRY 4.0 MEAN?

Today, people identify Industry 4.0 with the following main technologies: communication among machines, communication among machines and "things", big data, artificial intelligence (AI), cloud computing, decision-supporting systems and personalised mass production. (Sztrapkovics et al. 2019)

At most of the conferences, the discussions are about the opportunities these technologies hold and how the various industries can use them. For example, big data and cloud computing would allow us to analyse a great amount of data, then to optimise workflows according to that. We have the opportunity to make data accessible to stakeholders in a transparent way, and afterwards, we can visualise it in order to support their decisions. With artificial intelligence, we can decentralise decision-making, thus taking some of the burden off main decision-makers. For us, the question is not what we could use a technology for, rather if people are willing to use it. Are they able to use it? Do they prefer it to previous versions? Are they able to use it in teams? Have they developed an understanding of how to use it?

There is no question that, without technology, there would be no shift between eras. However, just because there is an opportunity for something, it does not mean it will be realised. Since the envisioning method in the discipline of future research (Nováky et al. 2017), we know that applying new technology depends on more factors than just inventing the technology itself. It is a necessary term, but not adequate. Let us see how the previous shifting of eras ran their course and what kind of conclusions we can draw from this, in order to get to determine how we can benefit from the opportunities of Industry 4.0 as soon as possible.

INDUSTRY 3.0 AND THE AEC SECTOR

For the most part, we date the first industrial revolution from the appearance of steam engines, and the second from the appearance of electricity, assembly lines, and mass production. With regard to Industry 3.0, we consider that it begins either with the invention of the transistor in 1947 or from 1969 - the birth of ARPANET (the ancestor of the internet) and the Intel 4004 chip.

The main inventions of the era were the computer, automated assembly lines, internet and personal computers. From the AEC industry point of view, automated prefabrication, computer-aided design, simulations of virtual buildings, and remote design collaboration appeared.

This technology allowed the spread of telecommunication, outsourcing, digitisation of analogue equipment, and thus globalisation. The main promise of this new era was that fewer employees were needed, while productivity would grow. If we look at the productivity of the US (Figure 1), we can see that it has truly multiplied. Still, it is interesting to take a look at the efficiency of the AEC industry compared to the rest. While the economy as a whole was characterised by steep growth, the AEC sector tends to show a slight decline. This trend has not changed in the last decades. (Figure 2)

Figure 1
Labour productivity index for US construction industry and all non-farm industries

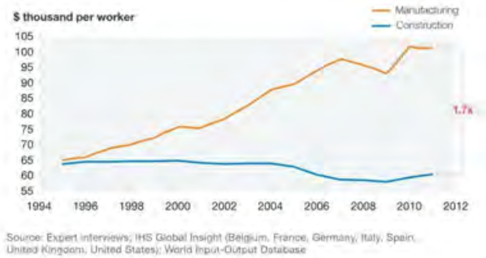

Figure 2
Overview of productivity improvement over time in the manufacturing and construction industry (McKinsey&Company)

This raises the question: Why has the efficiency of the AEC industry not grown? Could none of the technology provided by Industry 3.0 help the AEC sector? Alternatively, is it possible that the technology was available, but we simply did not implement it in the right way? Throughout our research, we looked for these answers, focusing on the design phase and design studios of the AEC industry.

RESEARCH CONCERNING THE TECHNOLOGICAL DEVELOPMENT OF THE HUNGARIAN AEC STAKEHOLDERS

During our research, we were interested in what kind of technology and workflows design studios have already implemented and what kinds they are planning to. What barriers they have to overcome during technology implementation. To this end, we collected information from three places. From these sources, we were able to map actual Hungarian circumstances.

First, the results of an already existing online form carried out by the Lechner Knowledge Center in late 2017 with 89 participants from the AEC industry. They asked respondents what do they use BIM for. It turns out that 56% use it for documentation, 45% for supporting the design process, 40% for quality checks. (Figure 3) These are the very basic functions of Industry 3.0, and barely half of the studios use these. Other functions are used even less.

One of the base elements of BIM usage is working with an appropriate 3-D featured CAAD application throughout the design process; no matter which brand of CAAD package is implemented and standardised by in-house rules and regulations. Hence an indicator of how organised they are working with BIM technology is if they are using CAAD templates. Only 42% said that they are using templates. The third fact that we would like to point out from this research is that lack of BIM education and training is a major setback factor for new technology adoption. (Figure 4) If we compare these results with the results

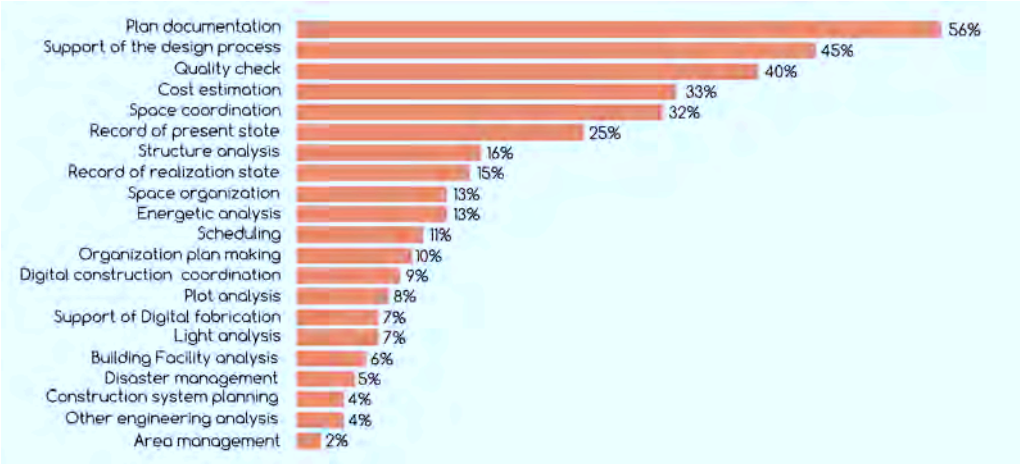

Figure 3
BIM use in the Hungarian AEC industry concerning function

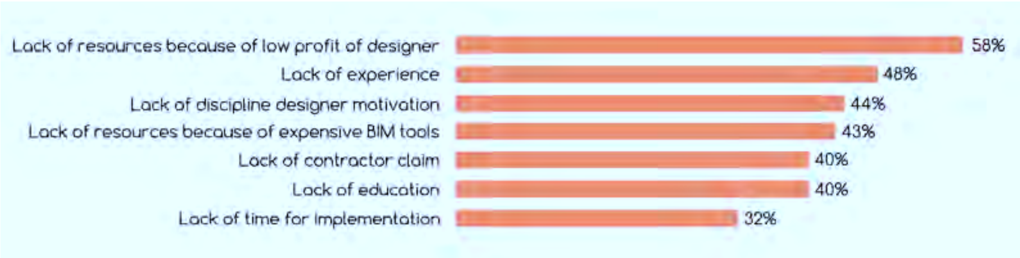

Figure 4
Top barriers of new technology adoption in the Hungarian AEC industry

from Poland, we see that there are a lot of similarities, which suggests our findings could be more widely valid. (Kepczynska-Walczak 2018)

Secondly, a BIM survey (Porkoláb et al. 2017) prepared by three of our students and filled out by more than 100 designers and discipline designers.

Although there are more valuable data collected in the research, we are highlighting only one part of it. In Figure 5, one can follow the answers of the respondents if they are using BIM technology, not using it, or planning on using it. 42% said that they are using it already, and 50% are planning to use it, whereas 20% are not even planning to use it.

The third area of research consisted of in-depth interviews with ten design studios from Budapest, Hungary. We have highlighted three thoughts they shared with us during these interviews.

- “To sum it up, during BIM technology adoption it is not the difficulty of using BIM tools that makes the process difficult, but creating new mindsets in our colleagues”.
- “Human communication plays a significant role and should be emphasised more, no matter if a BIM model exists, or no matter the design method”.
- “Regarding project management, for our employees, the most difficult part is to shift from their notebook to a digital tool.”

In addition, we wondered what kind of expectations Hungarian design studios have to meet in the era of Industry 4.0. Therefore, we conducted research on the future of Hungarian architectural design. (Kovacs 2018) We reviewed the forces that may transform the future of design in the next 20 years. There were two online surveys. One was filled out by 120 architects, whereas the other was completed by 160 people who were not familiar with architectural design processes but represented the “person in the street” who will affect it in other ways.

We asked the following almost taboo question: “Can you imagine a computer that can design your house or flat without an architect’s intervention?”

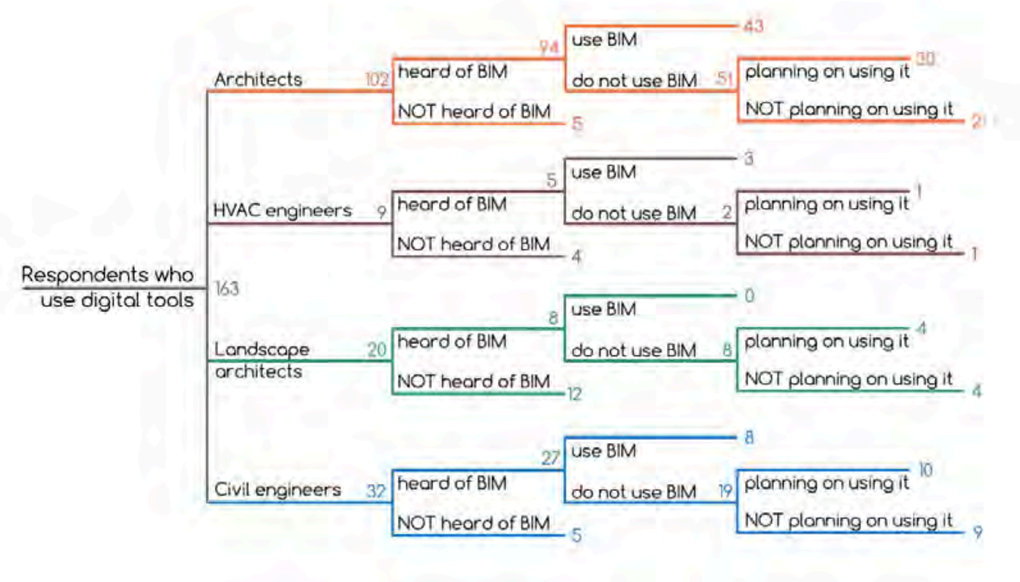

Figure 5
BIM attitude in the Hungarian AEC industry 2017

In response, 58% of the architects and 72% of the non-architects could imagine a computer alone being able to design a building in 20 years. (Figure 6)

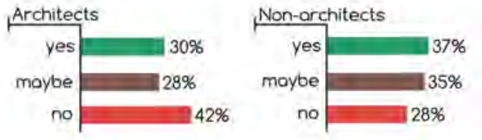

Figure 6
Answers for the question, whether respondents can imagine a computer designing a house or flat without an architect's intervention?

According to 35% of architects, the role of informatics and software skills will greatly increase. In the meantime, many commented that it is likely that programming skills will be necessary for architects. As for creativity, 18% said creativity is going to be more important in the next 20 years. 15% felt that soft skills such as communication, cooperation and emotional intelligence would be more important as well.

Summing up all of the results of the above researches, it appears that a great many studios see the future of design in Industry 4.0, but they barely possess the competencies to apply it. Furthermore, a significant number have not yet finished implementing Industry 3.0, even though that is a prerequisite of 4.0. They are struggling with adoption, and the barrier is not the lack of accessibility of technology, nor the quality of technology, but lack of education and workflows. If the digital company culture cannot keep up with the ecosystem of 3.0, then it is not possible to step up to the next level, because it is based on a maintained informatics infrastructure, databases filled with correct data, a culture of online collaboration, and mature human-computer interaction.

During our interviews, some architects considered buying new software and including half-day training as an implementation process. However, if we look at the implementation of technology from a socio-technical view (Arayici et al. 2010), it turns out it has three foundations. The first is the installation of the technology, which means installation of software and/or hardware. The second is the creation of workflows. The third is the development of the employees' skills and motivation. In order to have a successful implementation process, all three of these aspects are crucial. If there is no technology, there is nothing to use. If there is no correct workflow for employees to follow, then many errors and difficulties will interfere with the use of that technology. If the employees are not ready for the given technology, they are going to resist. This means, practically speaking, that it is not enough to buy BIM software. Use of the software must be taught, the employees must be prepared and motivated, and the used cases precisely applied.

There are several challenges that design studios have to face while undergoing development. These can be put into five categories: customer related, company related, social aspect related, technology related, supporting element related. (Tulenheimo 2015) BIM organisation development provides an approach to handle these matters together successfully.

BIM ORGANIZATION DEVELOPMENT

Nowadays, professionals and scientific society both call introducing new technology to design studios BIM (Building Information Modelling) implementation. We think using this term is not accurate and may be misleading about the significance of the process. According to the Cambridge Dictionary, implementation means: "act of putting a plan to action" or "start to use something". On the one hand, every company must develop its plan and strategy concerning the introduction of new technologies before they can put it into practice. So, in this sense, this process is more than just an implementation process. On the other hand, it may be misleading because it does not suggest how fundamental an effect it has on a company. This process contains several implementations of different technologies, and it is so complex that the whole organisation has to adapt to it.

Therefore, we prefer to call this process BIM Organisation Development because it better expresses the essence of the process. Organisational Development (OD) became a scientific discipline with literature dating back to the 1930s. "Organisation development is a systemwide application and transfer of behavioural science knowledge to the planned development, improvement, and reinforcement of the strategies, structures, and processes that lead to organisation effectiveness." (Cummings et al. 2014) We are merging the knowledge of OD with the knowledge of BIM and the latest digital technologies. We define BIM Organization Development as following: "It is a planned and systematic approach to improve the effectiveness of a design studio focusing on development of technology, workflows and employees simultaneously."

The market lacks services that give comprehensive business and process developments for design studios. Nowadays, design studios focusing solely on technological tools (Hochscheid et al. 2018) with maybe some hard-skill training is a good scenario. However, organisation development is as effective as the least developed part of it, so it is important to highlight the human factor of this development, which is not usually taken as seriously as it should be. It is possible to have great technology and efficient processes, but if and when it is put to use by employees, we may find that it does not work because of a lack of knowledge, lack of skills, or lack of motivation. Adopting new habits - and BIM OD is about creating and applying new habits - is one of the most difficult things in everyday life. Every employee has their own background and is going to experience this development as difficult or as easy accordingly. Hence, it is beneficial if we take their attitudes and personality into account in order to decide on the level of new technology adoption and how quickly we would like to finish the process. (Tulenheimo 2015)

We named our BIM Organisation Development process "Brick+Data Method". So far, we have used this method on three organisations: an 8-person studio, a 12-person studio, and the core team of the Hungarian Solar Decathlon Team, which consists of 30 people.

There are several approaches to BIM implementation. (Lindbald et al. 2019; Hochscheid et al. 2018) In our method, the audit is more comprehensive compared to other BIM implementation processes. We take into account factors, from hardware configuration to the personalities of the employees. Next, we believe that the facilitator of the BIM OD is crucial. They need to reach all of the employees and

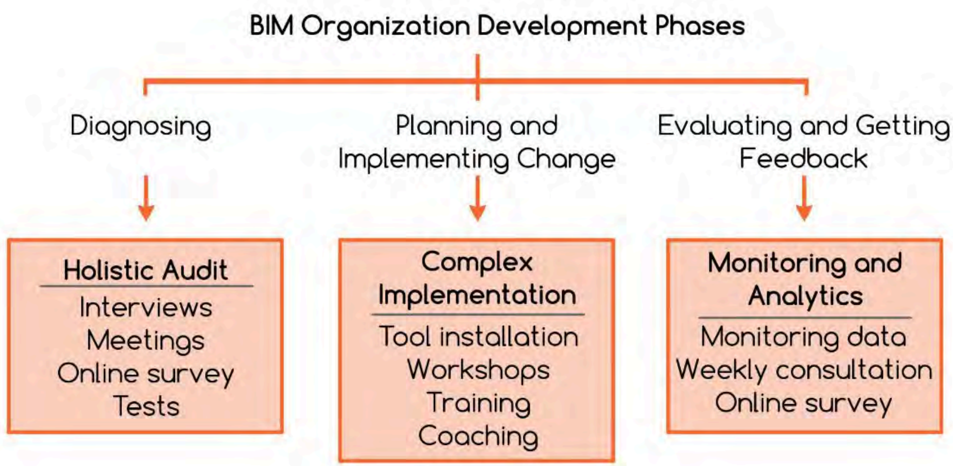

Figure 7
BIM Organisation Development Phases with Brick+Data method

earn their trust in order for them to learn new skills and change their habits. The facilitator has to be someone who has both strong hard and soft-skills and needs to have a respected experience in such development. Hence, we do not think a student intern would be an ideal choice for this! Our method includes the following three phases, based on the traditional OD steps. (Figure 7)

HOLISTIC AUDIT

To carry out developments on a design studio, we must first survey the level they are at the moment. Then, conduct a GAP analysis (Blokdyk 2017), which is a comparison of actual performance with potential or desired performance of the company. We do this in a holistic manner, which means we spread out the scope as much as our present knowledge allows us. We organise the audit under the same three topics: technology, workflows, and employees.

For the technology aspect, we benchmark the hardware park and a list of the software infrastructure. We analyse the file system and the nomenclature, and look at the templates used by different software, if they exist. Finally, we take office ergonomics into account. For example, in one case, it turned out that the bottleneck was not the BIM software or unsatisfying communication, but the uncomfortable chairs and small screens.

In the workflow section, we break down the design steps: proposition, project start, design, project closing, etc. We do not only take into account the procedures concerning the architectural processes, but all the business processes as well - for example, the inner team communication, whether it is a weekly meeting, emails, use of the calendar, or the use of project management software. It even includes communication with the discipline designers, partners, and marketing. At the HR level, we create an HR book where the surveys filled out by all the employees can be found: with the various aspects psychological profile, motivational factor, and soft and hard skills.

During the audit, we use different methods to collect data. We carry out personal interviews and hold focus-group interviews with different team setups. We fill out an online survey with the team and administer different types of tests: ARCHICAD or Revit, Excel, and DISC personality test.

COMPLEX IMPLEMENTATION

In this phase, we implement our development suggestions accepted by the leadership of the office. This has two important steps.

The first is that we work out the given topic closely with the employees during facilitated workshops. The person who is facilitating these is somewhat similar to a BIM-Agile Coach (Gless et al. 2018) except he is mixing other techniques beside agile ones. As a result of these workshops, descriptions, lists, and templates are created, which organise the studio. At the same time, employees internalise these while working on them, which will have a good effect when they start working in a new way.

The other is that we make a digital booklet for the operation of the studio. This is a collective knowledge base where we document the workflows worked out together with the company. This is fundamentally a collectively editable document, and anyone can add suggestions or comments over time.

MONITORING AND ANALYTICS

In the last phase, we explore how implementation operates in practice from the point of view of technology, workflow, and the employee. This phase is important because new routines need time to fully internalise in order to become a habit. It may also happen that an upgrade does not work as expected. In this case, we need to investigate it and modify it. We collect information regularly, both quantitatively and qualitatively, to carefully track the process.

CONCLUSION

In our paper, we conducted research where we identified that - at least in the Hungarian AEC sector - companies have not yet entered Industry 4.0, because they have still to adopt 3.0 fully. Our theory, based on our experiment, is that the reason for this lag is that companies focus only on technology, skipping processes and human aspects. Consequently, we propose that the key to entering Industry 4.0 is BIM Organisation Development.

We showed how we put this into practice with Brick+Data Method, developing all three aspects of the company. According to the studios we worked with, there were two additional benefits of the development what we could not see in advance.

The first was that during the focus-group interviews where we were supposed to get information about the company, the employees also heard a lot of new information. Their knowledge about the company, the processes and the motives and competences of each other synchronised.

The second benefit was that the big picture of the studio revealed itself to the leadership. During everyday work, leadership tends to get lost in the actual projects and tends to forget about the big picture and long-term goals. When they visually see the whole company from all the important aspects, it gives them a firmer basis for their decision-making.

Based on the monitoring phase of the development, studios we worked with became more organised and more efficient, closing the implementation process of Industry 3.0 and being ready to enter Industry 4.0.

FUTURE WORK

We continuously upgrade our method based on the latest BIM OD projects we take part in. One of our next steps is to carry out a detailed analysis on the comparison of our method to the BIMe Initiative [1]. Especially, the topic of measuring BIM performance (Succar et al. 2012) which gained our attention, because in our experience, making KPIs (Key Point Indicator) in certain parts of the development is a great challenge.

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Building Information Modeling for Participatory Decision-making Processes

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This paper presents and discusses the partial results of ongoing research on the development of computer applications connected to Building Information Modeling (BIM) software, aiming at the participation of non-technical actors in decision-making processes for public facilities projects. The research proposes the construction of a web-based application in which remote collaboration between technicians and non-technicians can be carried out in architectural design processes. The article points to the relevance of such cooperation in newly industrialised countries, reviews the key features of BIM, and presents the application currently under development. The paper focuses the theoretical discussion and characterisation of relationships between the involved parties and the practical implications of these reflections on the structure and design of the application. This research work is underway at the research group Nomads.usp of the University of São Paulo (USP), Brazil, and expects to contribute to the formulation and implementation of public policies in the sectors involved.

Keywords: *BIM, Participation, Public facilities*

INTRODUCTION

Participatory design and community participation in the decision-making process received considerable attention from urban planners and architects in the 1960s. This enthusiasm quickly led to a sentiment that participation hardly influenced final architectural results. Most of the times, communitarian participation appeared to be just a seal of approval issued by the community, more often than not compelled to choose between design proposals not representing its desires.

However, the ideals of participation grounded the thinking of generations of urban planners and architects. Lucien Kroll, in the 1970s, developed his principles of participatory design framed in extensive debates with future users, constituting pioneering initiatives of the effort of sharing design decisions with the residents. To accomplish such collaboration, Kroll made widespread use of physical models, and computer programs from the 1980s on (Bateli, 2015). It is, however, of Christopher Alexander the most incisive contribution to the computerisation of design processes aimed at the inclusion of the inhabitants. His book “A pattern language”, of 1968, became a significant reference in the area, mapping 250 patterns of human behaviour in the built environment, in the manner of design and organisational parameters. The works of Kroll and Alexander were precursors to the introduction of algorithmic thinking in architecture, and helped to construct procedures that would later be useful in the design of current parametric programs, especially those based on BIM. Their work range undoubtedly among the main references of the research on participatory processes in architecture, albeit in a somewhat mechanised and impersonal way.

In order to broaden and deepen the results obtained in previous works of Nomads.usp, and dialoguing with studies by Harvey (2012), Castells (2012) and Manovich (2013), among others, this research understands that the use of digital media - especially those based on Internet communication - can configure spaces of citizenship, community articulation and claim for rights. Of course, these media do not replace the face-to-face debate on the public scene but, associated with it, can constitute a hybrid territory - of concreteness and virtuality (Tramontano, Santos, 2013) - where substantial portions of urban life are developed. Likewise, such media may contribute to collective reflections on the importance of ensuring the implementation of the decisions taken therein, broadening its scope and its catalytic and articulating role.

This condition is particularly critical in countries of recent industrialisation, such as Brazil, where public policies for urban development are still under construction, and impunity for corrupt actions involving politicians and companies in the construction sector contributes to reducing the limits of government investment in public works further. However this scenario is slowly changing, with the examples of good practices such as the Participatory Budgeting program (Souza, 2001), laws that mandate the municipalities to establish thematic councils including the organized civil society to access the federal's credit lines and the online digital platforms used by several prefectures around the world, of which Decide. Madrid (https:decide.madrid.es) is undoubtedly a valuable reference.

In this context, the recent initiatives in Brazil to enforce the use of BIM in all public construction plans (Brasil, 2018) present an opportunity to further public involvement at the same time that it can help foster a culture of transparency and meaningful conjoint decisions. To contribute to the active participation of the population, the research presented here aims to expand the collaborative uses of BIM software in public equipment design processes, through the optimisation of communication among its actors and the inclusion of portions of the population with a direct interest in their results. They are: the inhabitants and merchants of the urban area in which the public equipment will be located; its permanent employees - employees and end users - public service employees involved, cultural collectives and associations of the Third Sector, public managers, political and private sector representatives, as well as technical professionals such as architects, town planners and engineers. In order to do so, the research benefits from four fundamental properties of BIM: 1. the insertion and visualization of information from building to design in a unique three-dimensional digital model; 2. the stimulation of communication among the various actors, allowing mutual monitoring and learning, 3. the registration and representation of information relating to the building throughout its life cycle, ie from the initial design to the occupation, adaptation and demolition phases, and 4 the possibility, at all stages of the process building, budget control associated with constructive elements and services. This paper identifies these actors and their relationships, aiming at establishing the potentialities and parameters that can help with the construction of a platform of collaboration between technicians and non-technicians in through the production process of public facilities.

DISCUSSION

The lack of predictability and transparency in the use of public resources is a pressing discussion in Brazil, especially in public construction projects (Santos, 2015), which leads to an environment where corruption and misuse of public resources can thrive. International experience and the literature indicate that to address this situation, a profound change in the production process of the public facilities is necessary. This change involves more factors than the isolated adoption of new tools or design processes, such as BIM, or the passing of harsher legislation - it needs the adoption of a holistic approach to the question, and the involvement of the community at large in the day to day activities of the governments is an essential part of this strategy (De Sanctis, 2015).

We understand that BIM is suitable to operate as a platform for the operationalisation of these changes since it presupposes a collaborative process, in which the information about the design, execution, operation and maintenance of a building is integrated and simultaneously available, subverting the current sequential logic. In this collaborative and integrated environment par excellence, where information flows in multiple directions, one can not speak, on the one hand, of compartmentalized knowledge, as in a conventional production line; this interdependence, on the other hand, generates the need for the rearrangement of the entire productive structure, since it also involves a shared responsibility. The impact of this platform is therefore more significant than just compliance with new rules and processes; it involves universes beyond the technical domain of Architecture and Engineering, interfering, as already said, in the economical, political and social spheres. This is statement is supported by several studies, such as Succar (2009), Sacks (2010), Linderoth (2010), Pentillä (2006), among others.

The Brazilian government's recent initiative to implement BIM (Brazil, 2017) as a federal public policy is important because, as policy maker and one of the main contractors of the field, it helps to shape and to catalyse the rate and the uniformity of the BIM's adoption process, lowering resistance and creating a clear timetable for its implementation (Wong, Wong, Nadeem, 2009; Cheng, Lu, 2015). This federal initiative is also important because in Brazil's cases of adoption by lower-level government bodies, inconsistencies, limits on applicability and conflicts with other actors in other fields were observed, resulting in a reinforcement of the resistances and objections to it.

This statement is corroborated by the fact that the federal legislation that regulates the all public bidding processes allows a great deal of uncertainty already in the the planning phase. The Law 8.666/93, which defines the procedures for public biddings, only defines in broad terms that it is necessary to have a "basic project" with information and degree of detail "sufficient" to start the bidding process (Brazil, 1993). These vague terms that fail to define precisely the required information open the door to a wide range of interpretations. The progressive reduction of the technical bodies of the public institutions, starting in the neo-liberal governments in the middle 1990s, and the existence of a large contingent of political indications of public workers (more connected to the individual administrations than the public service as a whole) creates the ideal framework for the actual scenario of corruption, waste and lack of expertise and unaccountability (Pita, Tramontano, 2017). Of course, we cannot attribute all the problems verified in public works solely to corruption; the failure to properly plan a complex enterprise such as the production of a public facility leads to a waste of resources, improvisation at the construction site and poor financial allotment. These questions, however, have a different nature than the corruption and misuse of the public resources; they can be mitigated with more precise standards and a tighter regulatory policy - uncertainty lowering actions that also benefits (but aren't sufficient to) the combat to corruption.

There is a direct association between this uncertainty and the problems discussed. At the heart of corruption, the processes are the basic question of power and control over information (Rose-Ackerman, 2004). The establishment of a prior agreement between the actors in the form of a secret that binds them at the same time that excludes others corrupts the republican relations that should prevail, based on the concept of transparency and accountability.

In fact, the word corruption itself in its Latin origins means "to break" and "heart", showing that a corrupt action is in fact an attack in the very core values of democracy and republic.

Sabet (2009) indicates that corruption is a "wicked problem", that is, a problem with undefined shape that adapts itself to the attempts to solve it. The author also states that the transparency of information and relationships among stakeholders is one of the few truly effective means of combat since the involvement of a large number of actors and groups and indiscriminate access to information destroys the very principle of the secrecy and opaque agreements between few. A secret is no longer a secret if there is no control over who knows it.

In this context, the research presented here aims to involve a greater number of actors in the production process of a public building. The introduction of these new actors leads to new behaviours and emergencies, which in turn can be incorporated into the ongoing process. To understand how such communication between actors with and without a technical background can establish a meaningful conversation, we used Gordon Pask's Conversation Theory and Edgar Morin's Complexity Theory as a theoretical framework, forming the basis for the understanding of the new proposed dynamics. These new dynamics bring with them a certain amount of unpredictability, which must be incorporated by the systems through clear standards since the excess of this unpredictability can lead the system to collapse.

This diversity, however, does not jeopardise the design process, quite the contrary. According to Morin, "their diversity is necessary for their unity, and their unity is necessary for their diversity" (Morin, 2005, p. 147). Thus, the more diversity there is in the profile of the actors and the roles they play, the more complex the system will be, and the more likely it is to develop a new organisation - an emerging phenomenon that can manifest itself as new ideas, products or new organisations. It is a question of favouring transdisciplinarity in the process, since even if it is considered that the myriad of professionals and disciplines that participate in the life cycle of a building possess diverse knowledge, this knowledge gravitates around the same subjects. Thus, non-technical actors contribute effectively to greater transdisciplinarity through an increase in the diversity of attributes of the actors involved. According to Nojimoto (2014), this diversity is manifested in the different visions of the world, experiences and knowledge of each actor. This new information manifests itself beyond the pure technical question, introducing other issues such as communication, work relations, motivations, personal interests.

The introduction of these new actors into the design process is not without difficulty. The high degree of complexity of a building's documentation can impede non-technical actors to have a proper understanding of the information, and to process it to have a meaningful conversation and contribute with new information. It is necessary to establish common communication parameters - a common language, which minimises the differences of understanding about the object. This language need not be only textual: Pask understands that in order for a meaningful transmission of this information to occur, to the point where there is almost certainty of a common understanding, there must be agreement among those involved in the use of a language. This language can be non-verbal, but have to possess a great semantic richness (Pask, 1976).

The architectural language is, par excellence, a non-verbal language, of great semantic richness. These characteristics must also be present, by extension, in any platform that aims to integrate these different actors. BIM objects can act as carriers of this semantic wealth itself, and the multiple ways of displaying the metadata contained in them (through geometry, or in the form of tables, or as graphs) allows the information to be understood more clearly between the different actors.

This "language" forms the basis of a common agreement, indispensable for this process of conversation. Continuing the parallel between the theory and BIM, by accessing the information contained in the database, interactions immediately occur - between the actor and the platform and between the actors through the platform. Whether by viewing conflicts or splitting work areas, agreements are signed at all times, in addition to the common platform agreement. However, this agreement needs to be learned or adapted to another form of communication, different from the one used in the traditional design processes, and therefore requiring changes in posture and mentality concerning object of work and the relationship between the actors. If the boundaries between traditional design phases overlap in the process of adopting BIM, the very boundaries between the actors also become less precise (Succar, 2009). This flexibility is part of the initial agreement to operate on the platform.

This process requires interactions between the actors and the building of diverse consensuses that will shape the project. In this regard, the BIM platform can be defined as a system that contains these subsystems in interaction, with a common, predetermined goal. The information management and mediation of conflicts system represented by a collective of applications, databases, networks, etc. in interaction (which we associate with the BIM system) assumes the role of the controller of the process (Morin, 2005).

This incorporation of non-technical actors does not mean that there is a dispersion of the original attributions of each stakeholder, quite the contrary. Just as the BIM framework foresees an exchange of information between specialities, with the preservation of individual attributions and responsibilities, this must also happens on the proposed platform. It is not feasible to imagine that there is a reversal of the participatory processes underway on the platform: it is not a matter of commending the decisions of the community, but of establishing an open dialogue between actors. Thus, the platform must be designed from and for these stakeholders, and their specific attributes.

These groups of stakeholders, though interrelated around shared interests and roles, are not homogeneous in their demands and interests. Each individual acts in their capacity within them, leading to the emergence of leaderships, opposition, consensus and dissent, which may be explicit or not. As an example, within the agents of the State, constituted by the political agents and civil servants, there is a constant conflict. This conflict is proper to the constitution of the modern technical bureaucracy (Weber, 1994), in a movement of opposition of the hierarchical subordination versus the apparatus of legality that imbues the elected representatives with authority. These conflicts occur in a veiled way, and not infrequently deviations from the conduct of these political agents come to light through denunciations and oppositions of the state bureaucracy itself. Still, in terms of representativeness, these two groups are equally important, as they represent the various facets of the State and their internal conflicts.

This same logic occurs in all groups, in a process of dynamic self-organization as exemplified by Castells (2013). The proposed characterisation reflects this dynamic because many actors considered as part of homogeneous groups ("the government", "the community", "technicians") that act in unison, in fact, are only bounded to the groups' common goal in a temporal basis. These groups' agency capacity emerges from the abilities and interests of the individuals, and not the other way around. The proposed platform also takes this into account, and while some assignments are given to different groups, the different platform dynamics are intended to surface and expose the conflicts and agreements within and between them, once more aiming to level the playing field between the distinct groups and actors.

MATERIALS AND METHODOLOGY

As already discussed, the production process of public facilities is Brazil is determined by a set of rules and legal regulations and by the broader context of the civil construction. On the one hand, there is legislation defining the entire process for contracting and acquiring any service and good, establishing a formal environment where all intermediation with the public power must necessarily occur.

In parallel to this formal process, there is a network of relationships and interests that define the decision-making capacity of the actors involved. These networks and chains were studied with the support of the literature and field observation of these processes, and confronted in their formal structure. The determination of these relations was based on the study of the formal governmental structure and recent cases of corruption in Brazil, not surprisingly involving large contractors, where the evident existence of a parallel route of decision making is present and necessarily not transparent.

Of all the characterised variables, are of utmost importance the technical capacity of these actors, that is, their intimacy with the language and the productive processes of a building. This criterion is fundamental, and characterised as a priority because if the information of the project is not understood in its nuances, there isn't already the establishment of a common language and the prior agreement of the conversation.

The second characterised variable is the articulation of these actors and the public sphere, since this determines their position in the formal structure of the productive process, indicating it position on the formal hierarchy, their decision power and controlling power.

Finally, the interest and economic capacity are important factors because it indicates the ability to influence decisions in an "informal" way, that is, to the detriment of the formal collaborative structure. This characterisation by definition is complicated and less precise since it involves frequently influence peddling, active and passive corruption, among others, which, due to their characteristics, have a non-transparent mechanism.

From the characterisation of these actors, the next step on the research was the development of a prototype of a platform with a common language and equal access to pertinent information, in order to allow a qualified dialogue, where emergencies may arise and new solutions and relationships established. To this end, the research is based on the concept of praxis, understanding theoretical reflection and practical actions of experimentation and application as inseparable and interacting. For this reason, it envisaged the construction of a computational application, in parts that are being tested several times in situations analogous to real ones. Each cycle test feeds back its revision, contributing to its validation and the legitimation of the procedures adopted, and at the same time subsidising new reflections.

RESULTS

The productive process of public works in Brazil is structured through the action of several actors around a specific legal framework. The demand for a particular work occurs at the initiative of the public agents and of the executive powers, through the action of public agents (ministries, secretaries appointed by the elected representatives) or elected representatives themselves (mayors, governors). These representatives demand the construction plans to the technical staff of the public entity, which in turn either prepares the first studies and the draft or contract it externally. These technicians act as an intermediary between the public agents, the outsourced contractors for the project and for the work, and, to a lesser extent, the community or the users of the building.

In another phase, these technicians act as intermediaries and representatives of the public interest when dealing with these contractors. These, in their turn, execute the contract and deliver the building to the municipality, which operates the facilities in benefit of the final users. This is the workflow as defined by the legal bills, and is generally a transparent and documented process, as seen in the figure 1. Also, in this figure, it can be seen the tenuous relationship with the community at large, be it comprised of technicians or non-technicians.

However, some other connections take place in this context. Communication between these actors not always follow this formal chain, and some parallel, and undocumented relationships develop. These relationships are charted in figure 2. It's important to notice that some of these non-official relations are also non-republicans, and form the basis of the corrupt or distorted relations that were discussed before.

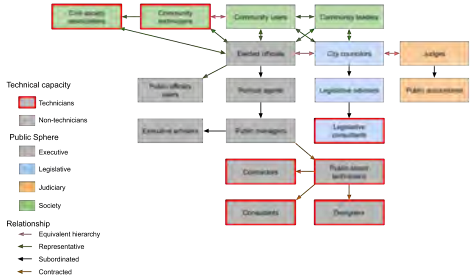


Figure 1
Formal relationships between actors. Source: the authors, 2019.

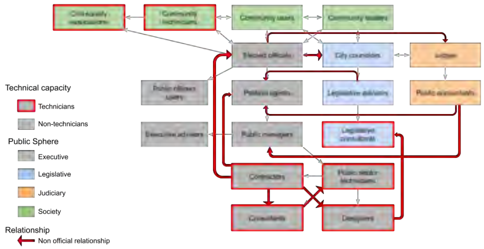


Figure 2
Informal relationships between actors. Source: the authors, 2019.

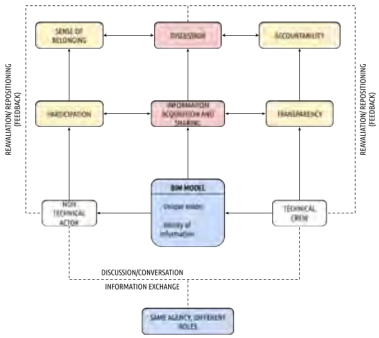


Figure 3
Conceptual information flux. Source: the authors, 2019.

The roles of the different actors are multiple, with the occupation of several categories. This result demonstrates the need to predict that the means and forms of understanding and access are multiple, and that there is a considerable contingent of stakeholders who have little or no contributory capacity in the current productive process.

The graphs show that despite the role played by technicians, the decisions do not always follow these criteria, and this dialogue is often directed by other means. The population and the users of the building generally don't have an active voice in the process, except at specific moments and linked to electoral interests. There are internal organising projects of these groups to maintain their hegemony and their position. This process is based on the control and capture of information by groups, which they share with others who share their ideas, in a secret pact.

The BIM as controller of the communication process has instilled in itself the premise of transparency and the accessibility of the information contained. Information niches diminish considerably among technical actors, and, according to our previous work, has the potential to extend this communicative capacity to non-technical actors.

In a way, transparency in the process stems from the very nature of the projects. The structuring of a coherent and productive conversation depends on the existence of a common language among the interested parties, a basic condition for discussion. Agreement with the rules of conversation is essential.

The figure 3 show the development and the platform concepts. This platform is operative in a prototype stage, passing through various stages of testing. It can be accessed at www.nomads.usp.br/bimnomads/en.

The proposed application derives and presents its information directly from the IFC file exported from the various BIM applications. This direct connection is important to minimise the possibilities of tampering or occluding relevant information, which can occur if this translation is delegated to an actor. This principle maintains the integrity of information, which can be verified in every stage of the process by the myriad of IFC checking and compliance applications.

This information must be presented in a meaningful way, and the platform makes use of adequate the more medium in every moment, without overwhelming the non technical user. For this end, the production process is divided in moments, analogous to the actual phases of project, but with a crucial difference: in every of these moments there are preferred subjects of conversation (implantation on the site, preferred spaces distribution, specifics needs of the community) but all information is available and presented in a simpler way, in the form of a simplified interactive 3D model and all metadata contained in the objects, comparative tables, etc. This helps the establishment of the common language.

Every one of these moments is open for the input of every actor, in the form of a parallel discussion about the current subjects (where the interactive 3D model is present to inform this discussion better) or in a completely independent forum where every subject can be discussed. This last forum is important to foment the self-organization of the different groups.

At last, the individual attributes of every actor are preserved in the form of the different roles they play in every moment. The discussion forum assumes the role of a public hearing of sorts, registering every manifestation contained. This status means that one cannot comment anonymously; the registration of the individual actions is important to generate a greater sense of responsibility and accountability. Also, every moment is divided in smaller moments where all objections and proposals must be answered by the public sector, being it by the technical actors, being it the representatives. This dynamic is necessary to preserve and to account for the attributions and responsibilities of every actor, and to create a meaningful discussion. In these moments, no new comments or discussion can be initiated by the community, but the general discussion forum is active throughout the entire process. These moments and the general structure of the platform are shown in the figure 4.

CONCLUSIONS

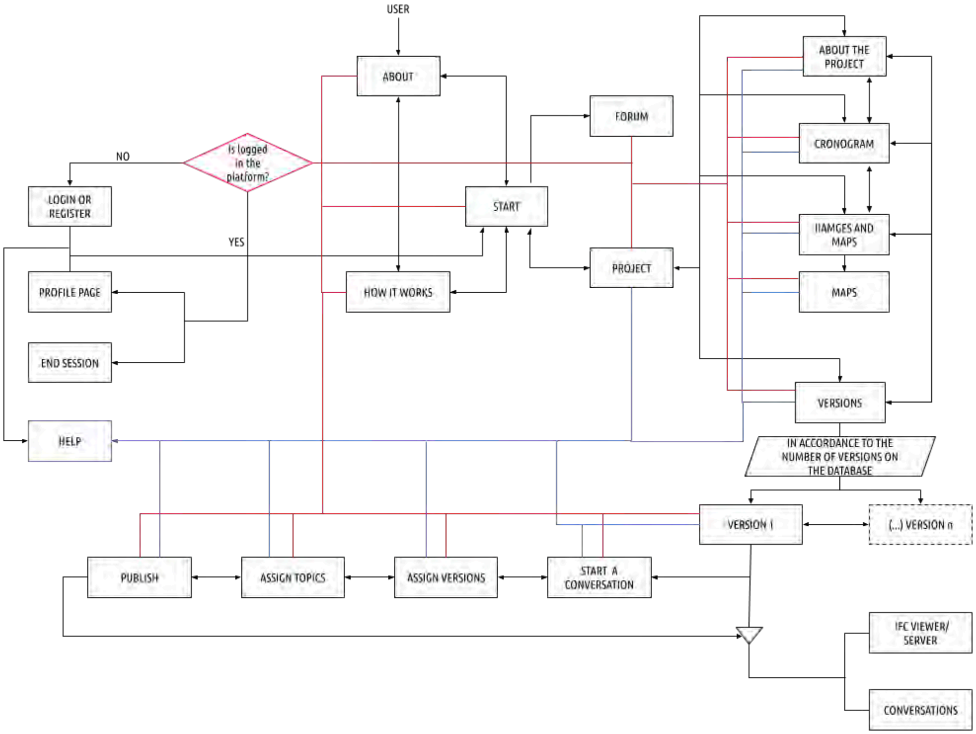
We reviewed the literature and through observation determined the groups of interest involved in the production of public facilities. These groups are not homogeneous and have internal dynamics and attributions that cannot be ignored.

We determined that accesses to information and the possibility of having an equal agency capacity is necessary to the platform, independent of the technical knowledge and the position and relation between them. To obtain this equality of conditions, the information needs to be transmitted in a common code, capable of constituting itself in a single language where the consensuses and dissensions can manifest without noises on the communication, initiating a dialogical process.

At the practical level, this translates into an interface that provides non-technical actors with the possibility of understanding the project and the work in its specificities and generalities, minimising the interpretative efforts on the part of these actors. On the part of technical actors, there is a need to preserve their role and responsibility. Finally, on the part of public managers, the function of mediation between society and the community must be maintained, since it is not intended that the platform be transformed into an instance of direct democracy.

The application also does not intend to replace or overlap with the processes of participation and control already established, but to operate in parallel with these, allowing the addition of a dimension to the involvement and collaboration of the non-technical actors. It is not ignored that the implementation of these processes depends on initiative and changes in the structure and form of the operation of the official bodies - for example, if the projects are not elaborated or contracted with the use of BIM by the government, there would be no possibility of interaction with the model required by the application. In addition, the space for debates must have attributions equivalent to those of a public audience,

Figure 4
General structure of the platform.
Source: the authors, 2019.



with a record of the actions and acts of all those involved, under the risk that the platform becomes only a propagandistic instrument or become just the legitimization procedure of pre-defined decisions, which is a common criticism of existing devices.

This participation is relevant not only to the constitution of a participative and fiscalizing culture of the State acts, but also as a means of including in the decision-making processes inputs and possibilities of new solutions that would not be otherwise available. In short, through this participation, new opportunities open up and the accountability of public agents is broadened, as well as a sense of belonging of the community at large.

Thus, the process that takes place at defined moments, where there is the provision of the information necessary to discuss the elements placed at each moment, with the availability of the three-dimensional model with the appropriate degree of detail. At these times, it is up to the administrator and public representatives to organize and encourage discussion, and provide general guidelines such as budget, available staff, etc; and the technicians, the obligation to respond and discuss the decisions taken with the other actors at every moment, in a transparent way. This discussion takes place in a single discussion forum, with simultaneous access to all the information about the project, whether these are textual, such as tables, schedules, budgets, or techniques, represented in the 3D model and the metadata associated with them.

It is hoped that this platform can add another layer of transparency on the discussion of a complex object as public spending in facilities. It aims to overcome a crucial problem in the effective participation of the community in its production process: the technical language barrier. The advent of the BIM opens up the opportunity for that overcoming, and its implementation have deeper significance for the public involvement, specially in countries where this participation is not common. The platform, however, cannot be a simple gimmick or a chancelatory step of the public decisions, with the risk of it becoming irrelevant in the long term. Thus, the intimate relationship with the BIM, being adopted at a federal level, and the status of the platform as an official public forum are important to achieve the aim of creating a relevant discussion, where emergences, transparency and accountability can happen.

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Design - COLLABORATION AND PARTICIPATION

Bridging the Gaps

Computation to Construction in India

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In the era of The Second Digital Turn, designers and engineers have easy and equal access to computational tools across the globe. With the highest development of technology at a global level, design development to construction process is locally contextualised in different parts of the world based on the available technology and resources. The paper presents a craft-based approach to computation and its contribution to support artisans' development in India. It is demonstrated through ongoing research on customising bricks and utilization of computationally generated asymmetrical Catalan vault. The challenge of constructing the computationally generated form by architecture students is completed by the craftsmen and students of crafts school. The research elucidates gaps at various levels. Craft based solutions bridging these gaps establish a methodology which makes complex geometry constructible in present-day India when access to digital fabrication methods are still evolving and expensive.

Keywords: *Digital Crafts India, Customising Bricks, Asymmetrical Catalan Vault, RhinoVAULT*

INTRODUCTION

In the era of The Second Digital Turn, designers and engineers have easy and equal access to computational tools across the globe. Big data sharing and advancements in digital fabrication with a six-axis robotic arm have revolutionised design thinking and making. Robots are being trained to sense information, feedback the process and take independent decisions like the craftsmen of the pre-industrial era.

The hands of Craftsmen have cumulative wisdom of materials, tools and techniques. A craftsmen's hands are directly connected to his/her mind. When craftspeople are introduced to new ideas (in this case complex geometry), tools and techniques (Catalan Vault), the construction process is as precise as machines. In addition to that, a craftsmen's knowledge and sensitivity to material and making bring an inherent quality without any pre-programmed instructions given to them.

BACKGROUND

Presented paper is part of ongoing research on customizing brick. The research looks into bricks with two simultaneous yet separate approaches.

The first approach - parts to the whole, is focused on the development of customizing building block (brick). Individual masonry blocks are customized to enhance the quality of existing brick. The aim is to make construction without mortar and/or add one of the qualities such as acoustics, thermal insulation, light and shadow on the facade, integration of plantation, etc. Customisation of the block can also be based on self-assembling complex geometries.

Whereas the second approach - whole to parts, is based on a funicular structure. Here, the form is computationally generated and the parts are considered as standard blocks available in the market. The focus is to design and build an asymmetrical vault at an affordable cost in India. The project conferred here is built based on the second approach.

The project conferred here is built based on the second approach.

CONCEPT DESIGN

Form finding

The project was conceptualized by students in a 3-week (Winter School 2016) course, Digital Crafts: Customised Bricks 1.1, conducted at Faculty of Architecture, CEPT University, Ahmedabad, India. Students were free to choose a specific site and program on Sabarmati Riverfront edge. A bounding box of the volume of 30 cubic meters (3 x 3 x 3 m) with the possibility to stretch the box keeping the same volume was given to start. This changed to 270 cubic meters (10 x 6 x 4.5 m) while developing the design.

RhinoVAULT which is the Plug-In to Rhinoceros® emerged from research on structural form finding using the Thrust Network Analysis (TNA) approach to intuitively create and explore compression-only structures was introduced as a generative tool. Number and type of supports were site-specific. Five different designs were generated by students working in a group of two. Out of these, children's play area was chosen to develop further [Fig. 1].

Design development

The plan footprint of 9.5 x 6.0 m with 5 boundary supports, two central supports and two cut-outs were fixed. Two central supports to include the details inspired by the teardrop columns (Frei Otto). The allowable maximum height was limited to 4.5 m. Height in some portion was further reduced to 1.8m so that children can climb on the roof and slide down from one of the central support. The form was iterated till all the headroom clearances were achieved with respect to the maximum allowable height and overall aesthetics of the geometry was resolved [Fig. 2].

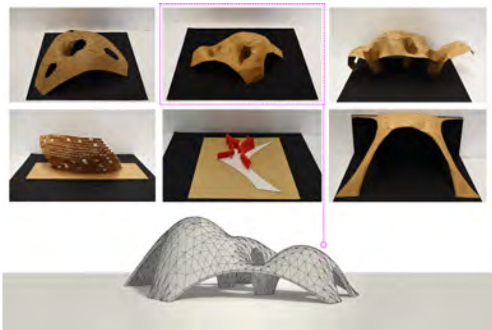

Figure 1
Design options generated in RhinoVAULT. Paper models made using Ivy for Grasshopper

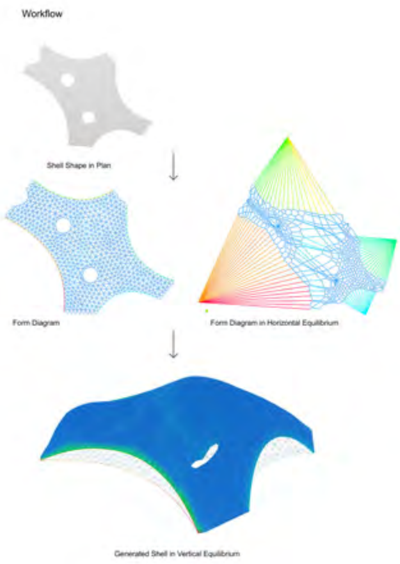

Figure 2
Form finding in RhinoVAULT

Figure 3
Diagram of construction sequence

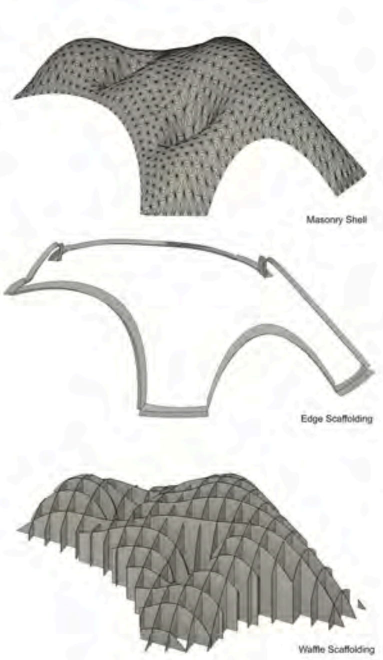

Figure 4
Students making Prototype (Scale1:5).

Prototyping (Scale 1:5)

A stepwise sequence of construction was referred from IaaC pavilion (BRG). Step 1, Make a visual guide using cardboard. Step 2, Construct boundary curves using scaffolding. Step 3, Build a masonry shell using MDF bricks between the boundary curves using a visual guide only (without scaffolding). Step 4, Begin construction from the ground to top from all five outer support points. Step 5, Begin with central support once the masonry work from outer support has reached the maximum limit of cantilever without scaffolding. Step 6, Complete the masonry shell on the top [Figure 3].

Students were obliged to build a scaled prototype (scale 1:5) following the set sequence of construction to understand shell behaviour during construction [Figure 4]. Simultaneous attempt to build a dome using standard brick (230 x 115 x 75 mm) and gypsum plaster. Cardboard visual guide was removed and the prototype was presented in the exhibition. This marked the end of Winter School.

LEGAL DIRECTION: ACADEMIA TO PRACTICE

The outcome of Winter School was presented to Ahmedabad Municipal Corporation (AMC). The authorities appreciated and encouraged the research by offering land to build this permanent structure in a park called Shahibag Riverfront Park, located on the eastern bank of Sabarmati river. However, the city engineer demanded us to submit the following as regular formalities for building permission:

- Structure stability certification along with the report describing load calculations and test results by an authorised engineer. {Notes: Dead load, Live load, wind load and seismic load}
- Fulfil safety norms for such structure in the public domain.
- Detail 2D working drawings including the cross-section detail showing multiple layers of construction and material specification.

The submission requirement is based on conventional construction and socio-cultural context.

CHALLENGES

At this moment in research, there were three biggest challenges: One, detail structure design and certification by an authorised engineer. Two, find craftsmen to build Catalan Vault without scaffolding. Third, limited fund.

Detail Structure Design and Certification by an Authorised Engineer

Funicular structure is a very well taught theoretical concept among engineering schools in the country, yet, equally uncommon and risky to certify in practice. Auroville Earth Institute has excelled detailing structure design and construction of symmetrical catenary vault in compressed earth blocks (Ref.). The only simultaneous ongoing project of its time in the country by sP+a used RhinoVAULT to generate asymmetrical form was also facing exactly similar challenges (Ref).

For detail analysis and verification, the mesh of the generated geometry was transferred to STAAD.Pro. A software most commonly used and trusted by engineers in India. The results were found common and safe, yet, there was a lack of confidence because there was no such structure built and tested till the date. Therefore, the engineer who verified calculations for the project did not certify the design for structural stability.

To find craftsmen to build Catalan Vault without scaffolding and reinforcement

Masons have excelled constructing domes by corbelling bricks. The technique is mastered over generations since its introduction by Mughals in India. Very few masons can build shallow domes using Catalan Vault techniques. This requires to be constructed within a continuous boundary condition - beam. Rise of such domes is not more than 8 inches. These are most commonly used to construct brick slabs.

Finally, Philip Block (BRG) was contacted by the author to guide construction (meeting in person at Fabricate 2017 Conference). The answer was, "construction of Catalan Vault without scaffolding and reinforcement is highly dependent on skilled masons. If one doesn't find, one has to train them".

Limited Fund

Till the date, there are no dedicated funds to conduct research in architecture, specifically in the domain: computational design and digital fabrication. This is a less known field. CEPT University funded the entire project, but the amount was less than USD 10,000. Therefore, neither the appointment of international experts as consultants for structural certification nor importing master masons to show construction technique was not possible.

Resolving these challenges was the longest and low period of 6 months.

CRAFT: BRIDGING THE GAP

The solution to these challenges was found from Craft Institute, Hunnarshala Foundation located in the western part of the country. The institute was also researching on Catalan Vault construction during that period. Masons of Karigarshala were trained to build a smaller (1.5 x 1.5 m), symmetrical vaults. The failure pattern was studied by physical load testing. Joint research between the two institutes was established to work further.

Data Transfer

Along with the .3dm model, a complete set of 2D drawings [left part of Fig. 5] were given to the team. One of the architectural interns handled 3D model. The curvature of each section was studied for detail structure analysis [right part of Fig. 5].

Material and Construction Detail

The first decision changed was the choice of material. It was recommended to use thin clay tile (fired) measuring 230 x 75 x 12 mm instead of the standard brick module which is 230 x 115 x 75 mm. This was simply to reduce the dead load of the structure.

The assumption was made that a minimum of 3 layers of construction will be required. First layer with clay tile and gypsum mortar to achieve the desired shape. This will be plastered with 25mm thick ce-

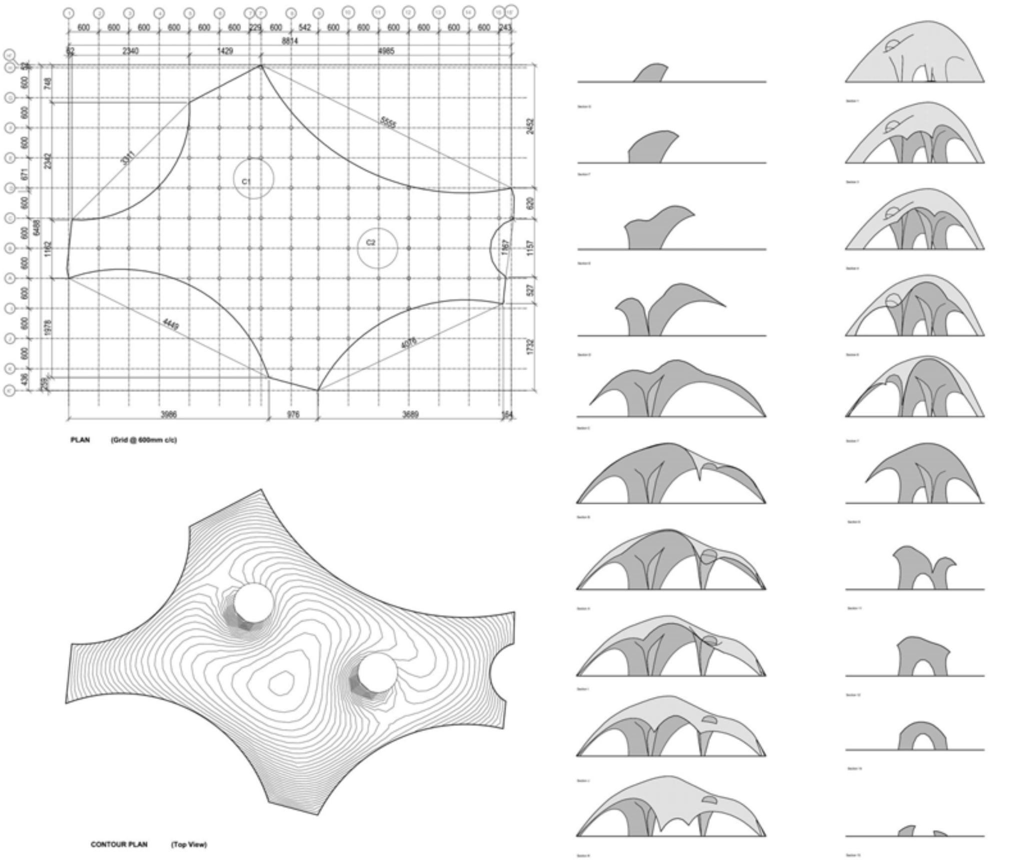

Figure 5
(upper left) Plan view of projected boundary curves on the ground with grid 600 x 600 mm (lower left) Contour layout (right) Sections at grid line A to I and 1 to 15

ment mortar on both sides, top and bottom. The second and third layer of tile on the top and the bottom to be constructed with fine cement mortar (ratio 1:2) to achieve the desired strength and protect the first layer from weathering and collapsing. More layers could be added, if required, after load testing.

Prototype (Scale 1:1)

The decision to build a prototype (scale 1:1) to train the masons as well as for physical load testing was taken. The construction sequence followed by students to build Prototype (Scale 1:5) was explained to the team of craftsmen and students of the craft school. Referring to the Drone Port Pavilion [Fig. 6], the making of visual guide differed from the earlier one made in cardboard. Advantage of the visual guide made of pipes allows workable space from the bottom.

Training Masons. Due to the asymmetric geometry and sharp curves of the form, it was further required to increase the precision of the visual guide. Therefore, the plan grid at 600 x 600 m was revised to

300 x 300mm. The perpendicular distance from the ground to the required surface was given at the intersection of the grid [Fig. 7].

Arches were built first, followed by surface, starting from all five outer ground points at a time. Tiles were precisely cut and shaped wherever required to achieve accurate double curved surface. Preparation of small portion of gypsum mortar was key to hold tiles in its location in space [Fig. 8].

Construction of teardrop columns required a special set of drawings [Fig. 9] to build the geometry. Figure 10 shows a piece of craft, marking the end of training the masons and construction of the prototype.

Figure 6
The Droneport Pavilion, Venice Biennale 2016

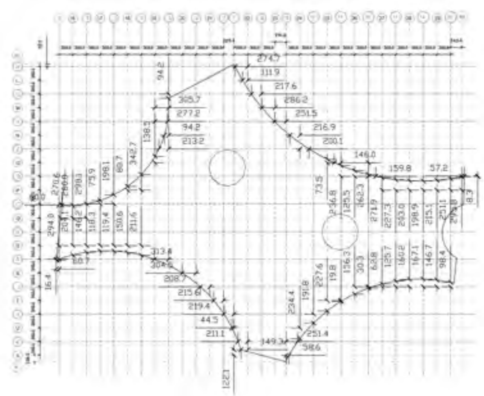

Figure 7
Revised plan Grid at 300 x 300 mm with vertical distances at intersection

Load Test. A total of 6 tons of load using 300 sandbags weighing 20 kg each were uniformly distributed over the surface area of the structure [Fig. 11]. Measuring tools were set on the centre of each arch and at regular intervals inside the structure to monitor deflection. The set up was left undisturbed for 7 days. 3mm deflection was documented. The same was confirmed to have matched with the computational model.

The entire process from foundation to load test was documented on a daily basis. An extensive structural report was made for the local corporation.

ONSITE CONSTRUCTION

Area of intervention was baricadded for safety of people visiting park on daily basis. The construction on site followed exact same sequence as earlier [Fig. 12]. Individual foundation for each support was done in brick with a waterproof plaster.

On-site Decisions. The decision on the orientation of pavilion in the park with respect to Sabarmati river, view from a nearby bridge, entrance area and pathway besides was made on site. Addition of seats, detail for rainwater drainage from the teardrop column, the landscape around and pockets for lighting were also made on site. All the additions made due to the capability and experience of craftsmen who could build just from a sketch. No working drawings, models or details were produced for this.

CONCLUSION AND WAY FORWARD

Construction Industry and Cultural Acceptance. Though India is known for its Information technology contribution to the world, it takes a decade or sometimes, even more, to percolate technological advancements in architecture and construction industry when compared to the global status. We are now in the first digital turn and India is still a labour-intensive construction industry. The cost of digital fabrication is still too high when compared to the cost of manual labour (craftsmanship). Often, the time taken to complete a project is not considered as the biggest resource hence it encourages craftsman-

Figure 8
Craftsmen training while building the first layer of construction

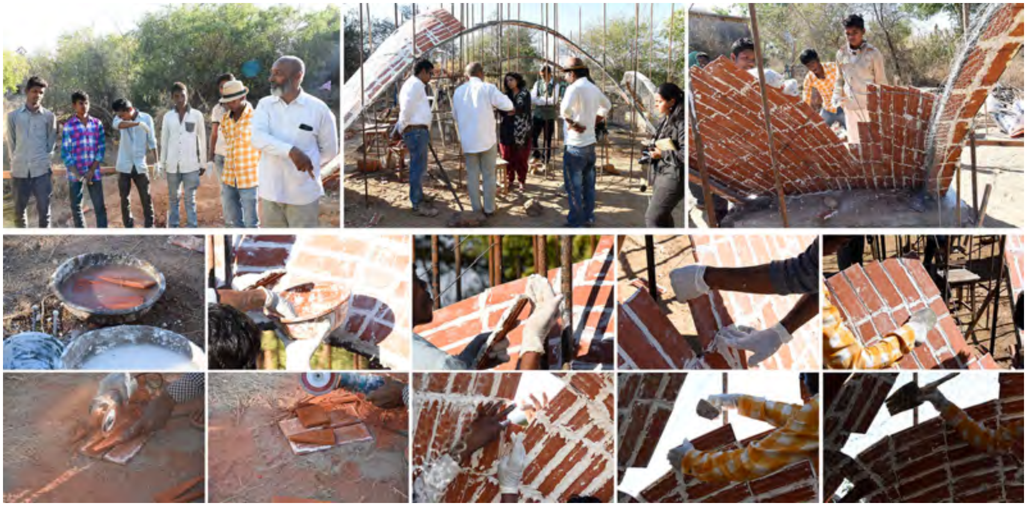

Figure 9
Drawings for two teardrop columns

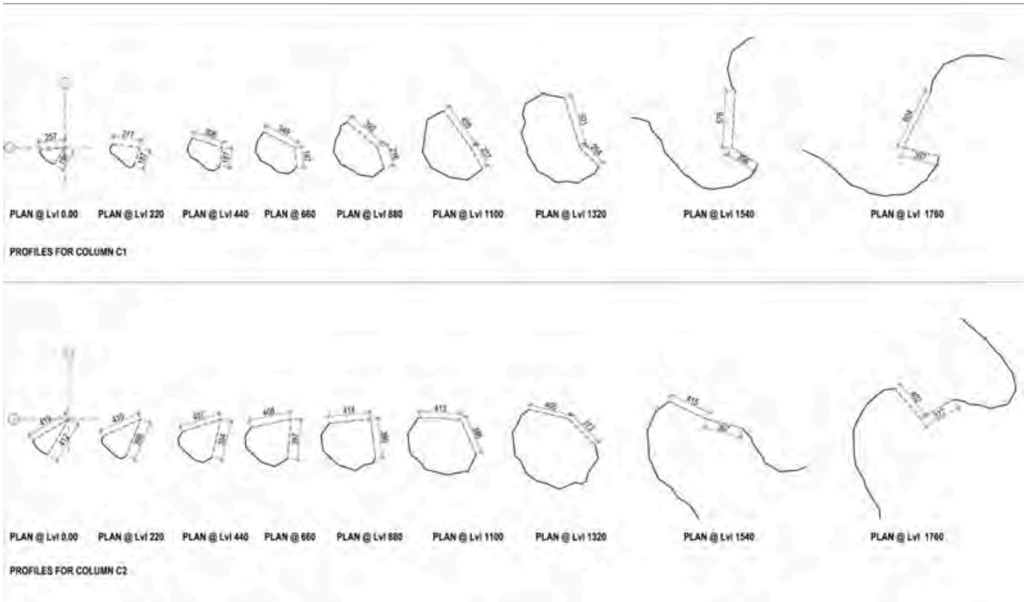

Figure 10
Prototype ready for load test

Figure 11
Physical load test similar to the thin concrete shell by Candela.

Figure 12
Construction on site

Figure 13
Additions on site

ship and speed of work delivered by the machines become obsolete. At present, it is most efficient to establish a balance between digital fabrication and craftsmanship to build a project with complex geometry.

Architecture, Engineering and Craft Education. Awareness of the advancements in technology and shard tools among designers/architects in India is relatively at par with the world. Architecture and design schools conduct a full-time course and/or specialisation in the field. Architectural practices also began to accept the digital turn positively.

There is a clear demand for updating civil and structural engineering education. Analytical methods taught and practised by the engineers are extensive, accurate yet not enough to be able to share mutually between designers and engineers. These methods are limited to symmetrical shapes. To be able to calculate the structural behaviour of asymmetrical free-form without digital tools in today's time will demand alternative methods, similar to the one used by Antoni Gaudi, Frei Otto and Phelix Candela.

Vocational training like Industrial Training Institutes (ITI) in India and Skill development schools like Hunnarshala must include construction craftsmanship like masonry, fabrication, carpentry and other related subjects. Skilled labour and educated craftsmen can change the face of the Construction Industry in India.

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Tornado Pavilion

Simplexity, almost nothing, but human expanded abilities

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In the context of the fourth industrial revolution, not all regions have the same access to technology for project development. These technological limitations do not necessarily result in worst projects and, on the contrary, can stimulate creativity and human intervention to overcome these shortcomings. We report here the design of a small pavilion with scarce budget and an ambitious goal to qualify a space through tactical urbanism. We develop the project in a multidisciplinary partnership between academy and industry, designing, manufacturing and assembling Tornado Pavilion, a complex structure using combined HIGH-LOW technologies, combining visual programming with analog manufacture and assembly. The design strategy uses SIMPLEXITY with ruled surfaces strategy to achieve a complex geometry. Due to the lack of automated mechanical cutting or assembly, we used human expanded abilities for the construction; instead of a swarm of robots, we had a motivated and synchronized swarm of students. The pavilion became a reference for local population that adopted it. This process thus shows that less or almost nothing (Sola-Morales 1995), need not to be boring (Venturi 1966) but less can be much more (Kolarevic 2017).

Keywords: *Simplexity, CAD-CAM, Ruled Surfaces, expanded abilities, pavilion*

Tactical Urbanism approach

This project is the result of a commission for an urban structure under the concept of tactical urbanism using new generative design and manufacture methodologies. The intervention took place in the Technological Park of the Federal University of Rio de Janeiro (UFRJ), a modernist site that lacks small-/medium scale structures to bringing personality and life outside the corporate buildings in the park. Located on the shores of Guanabara Bay and away from University City access, outdoor space is empty for daily use, as their users rather stay inside the buildings. Thus, the outside environment of the Park is not appealing for the users that do not appropriate these wide public that lack a sense of bellowing.

To develop this project raised different challenges: the macro coordination of institutions and industries, the need from the professors to propose a new discipline, defining the teaching methodology and to achieve the construction with few resources.

This article reports the process of design, conception, manufacture and assemblage of the Tornado temporary pavilion. We developed the structure in a multidisciplinary activity between undergraduate and graduate students in the areas of architecture, design and engineering under a partnership between the Laboratory of Models and Digital Fabrication (LAMO) and the Laboratory of Temporary Interventions and Tactical Urbanism (LabIT), the Postgraduation Program in Urbanism (PROURB), the UFRJ Technological Park and the Faculty of Architecture of the University of Lisbon. The project development happen under an optional course (PROURB) during the university first semester, the manufacturing occurred in September included in a workshop and the UFRJ Technological Park supported the material acquisition.

In short, the discipline, intended to implement a multidisciplinary collaboration method, combining expository and practical classes with contents involving tactical urbanism, temporary interventions, parametric design and digital manufacture. The students organized in mix undergraduate and postgraduate students from different careers to merge different visions and specialties in the same team. We requested a flexible project, economically feasible according to the supplied materials.

This work led us to rethink on the theoretical basis of how to "take milk from stone", or how to use SIMPLEXITY to materialize a complex geometry.

The Tornado Pavilion - was selected between 4 proposals, from 5 groups of students and built in September 2017; To accomplish the pavilion we had 67 grasshopper versions, 5 mockup models, 1 digital file, 600 wooden slabs (Dimensions of 4 cm x 8 cm with 3 m length), 660 circular spacers, 1440 type A screws, 1360 type B screws and 40 infinite-screws, 8 days of manufacture, 2 days of assembly.

The group of the selected proposal conceived a temporary pavilion to re-signify the vacant space providing shade and seating spaces, occupying the abundant free space. According to specific characteristics of the space, they positioned the structure obliquely, as close to the Park entrance as possible, connecting the entrance with a bus stop, crossing a future public square and creating an iconic reference for the users.

The pavilion opening was in 21th September 2017, in the context of the opening of an outdoor Art Space Gallery (Galeria Curto Circuito) that announced and gave wide visibility to the project, both for the academic community and for UFRJ Technological Park users. The pavilion was immediately appropriate and the structure spread quickly on the social media, attracting people from different academic units who had never visited the place, as shown in the following records.

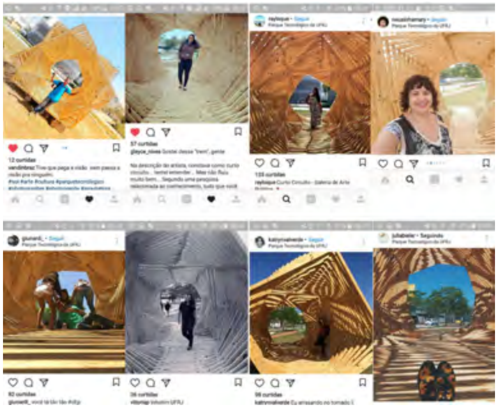


Figure 1
Tornado on the social networks promoting local empowerment

The concept of tactical urbanism refers to an approach to build and activate neighbourhoods using short-term, low-cost interventions that allow the immediate recovery, redesign, or programming of public space for future transformations (Lydon and Garcia, 2015). Applied in the field of urbanism, the term is recent (decade of 2010), however, its origin is in the writings of urbanist and French philosopher Michael de Certeau (1998). Certeau establishes the difference between strategies and tactics, calling strategy the calculation of power relations from the power point of view, and “tactics” the gradual reaction that takes advantage of “occasions” and the loopholes to act.

It is a small-scale approach related with bottom-up and Do-It-Yourself processes, allowing the student or professional to work “close to the ground”, reinforcing their social responsibility and encouraging cooperation with other professionals and society (Sansão-Fontes, 2018). The actions that respond to this approach operate tactically in a partial and agile way, serving to test an idea and its support by the community, in a process of trial and error. Acting in steps, prevents large investments that do not have the ultimate guarantee of success.

The particular feature of some tactical interventions is their temporary dimension. Named as “temporary interventions” (Sansão Fontes, 2013), these actions value transitory as a strategic quality to explore the place possibilities, seeing the city as a laboratory for testing ideas in real time. In addition, we can consider temporary interventions as breaks in everyday life, intentional moments to break the routine.

We based the intervention in the Technological Park in these premises, in a strategy coherent with the profile sought by this institution, precisely open to innovation and the articulation between different disciplinary fields and between university and companies. The Park emerges as an arena of mobilization of several technical innovations, with high infrastructure and technology, being the place to stimulate both young entrepreneurs and large companies, who can benefit from the supply of skilled labour.

LESS FOR MORE

According to Montaner (1996) Less is More is uncertain, but Mies' most used slogan was Beinahe Nichts or ″Almost Nothing″. Montaner in his book on minimalism points out that the ″less″ is inseparable from the ″more″, an ambiguous and contradictory dialectic, ″Less is more denotes a unity, neither of the two terms can be separated from the other, as they cannot be the day of the night, the light of darkness, the life of death. ″

Kolarevic (2016), with a solid theoretical foundation, explores this ambiguity and makes it a wordplay, mixing “simplicity” and “complexity” to define some other categories of performance::

Table 1
Kolarevic (2016)

SIMPLEXITY AND COMPLICITY		
simplexity	arising from complexity = complicity	Complex form part of simple rule
complicity	Simplicity arising from complexity = complicity	Simple form of "complicated" fabrications

Complicity

Kolarevic (2016) points to a mutualism, that is, to hybrid interventions that necessarily become interdependent. This posture makes him say that it is reductive the thought that postmodern sciences point to complexity and the modern sciences to simplicity. In a sense, Venturi (1966) anticipated this situation in his book Complexity and Contradiction in Architecture, when he pointed out the need for a third way, or “several” third ways as opposed to a situation of binary opposition.

″Architects can no longer afford to be intimidated by the puritan moral language of orthodox Modern architecture. I like elements which are hybrid rather than ″pure,″ compromising rather than ″clean,″ distorted rather than ″straightforward,″ ambiguous rather than ″articulated,″ perverse as well as impersonal, boring as well as ″interesting,″ conventional rather than ″designed,″ accommodating rather than excluding, redundant rather than simple, vestigial as well as innovating, inconsistent and equivocal rather than direct and clear. I am for messy vitality over obvious unity. I include the non sequitur and proclaim the duality.

I am for richness of meaning rather than clarity of meaning; for the implicit function as well as the explicit function. I prefer “both-and” to “either-or,” black and white, and sometimes grey, to black or white. A valid architecture evokes many levels of meaning and combinations of focus: its space and its elements become readable and workable in several ways at once.

However, an architecture of complexity and contradiction has a special obligation toward the whole: its truth must be in its totality or its implications of totality. It must embody the difficult unity of inclusion rather than the easy unity of exclusion. More is not less." (Venturi, 1977)

This contradiction is evident when the minimalist concept of almost nothing sometimes implies an enormous and complex projective effort. We can refer here as an example to the dematerialization of the windows of the living room of the Tugendhat house of Mies Van der Rohe in 1930, if we think of the design features, too sophisticated for the time, that were made to attain the results. Mies elaborates here a hidden and very complex mechanism by which the window of the whole room of the house descends to the subsoil and thus dematerializes in this "almost nothing" desired. The window is magically reduced to nonexistence, so we find a hidden mechanistic complexity used to support the conceptual simplicity of "almost nothing".

Solá-Morales (1995) in his article "Mies Van der Rohe y el minimalismo" proposes that the work neither evokes nor appeals to anything other than itself; is self-referential, and at most only makes explicit its materiality and its evidence. Without seeking any meaning it refers, and ends in itself.

This in part coincides with Montaner's (1996) classification with the idea of Pure Present, which again evokes self-referential, the lack of meanings (without allusions) and the anti-historical condition, thus seeking the notion of eternity.

The quest for almost nothing here is fundamentally of aesthetic order, and to make it, uses complex design mechanisms. Kolarevic defines this resource as COMPLICITY, in which the simple form is the result of complex fabrications, however, here complexity and simplicity cease to be antagonistic and begin to work in harmony in a hybrid consensus, whereby aesthetic simplicity depends on the complex design.

MINIMALISM		
1 Minimal Picturesque	Contextual Chromatisms	Atmosphere of Place
2 Geometric Rigor	Geometric shapes and patterns - Formal economy	Maximum formal tension with minimum means
3 The ethics of repetition	Repetition of the identical tending to infinity	Serial systems that eliminate hierarchy
4 Technical accuracy and materiality	Conception as pure technique and mechanical precision	Aesthetics that emanates exclusively from materiality
5 Unity and simplicity	Existence is limited to the essential	Austerity and compositional rigor. With indissoluble and indivisible elements
6 Scale Distortion	Strange, non-relational, self-referential scale	Predominance by size and perfect repetitive treatment of the skin
7 Predominance of structural form	Structure as aesthetic-constructive apparatus	that conveys a sense of eternity
8 Pure present	Self-referential, without allusions, anti-historical	Narrative and phenomenological experiences

Table 2
Montaner (1996)

Simplexity

In the construction of the Tornado the idea of almost nothing or less is more - reinforced by the approach to tactical urbanism that is based on resource saving - enter both in design and manufacture, and are adjusted throughout the process. In this sense, we oriented the design development towards ruled surfaces, to face material and manufacture limitations; we requested wooden joists with screws connections.

The Tornado fits within the precept defined by Kolarevic of SIMPLEXITY, by which it presents a complex form that arises from the exploration of topological formative models (Oxman 2006), a twisted cube, (Fig.2), however, the result arises from the use of simplified design and manufacturing rules. The project begins from a line (that becomes a slab) of 3 m in length that performs simple serial operations of movement and rotation to define the form.

Figure 2
Topologic formative model in Carmo (2018)

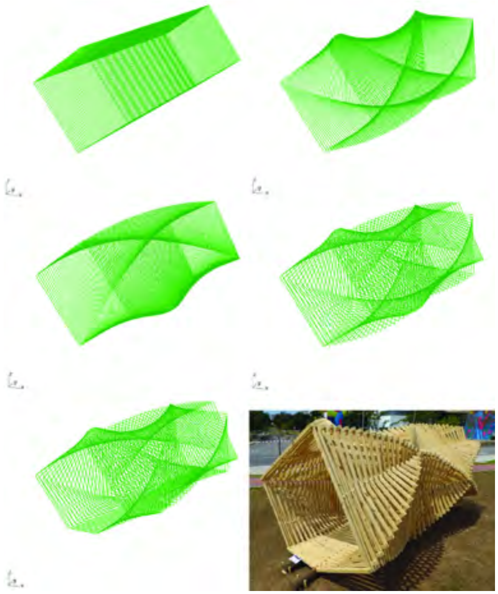


Figure 3
Capture of the kinetic development: 1 Move in series, 2 rotation CW, 3 rotation CCW, 4 base form, 5 ground section, 6 result

During the design process, we move from the topological formative model to a generative based model of simple grammatical transformation (Fig. 3). This situation occurs during design, from the moment we apply series of commands to a single primitive. (Oxman 2006). In addition, we did the manufacture in the same way as the design, that is, with a superposition of lines that form frames and rotated frames. The only prerogative that we allowed ourselves to break this condition was the execution of the floor, in which the design starts from a horizontal section in the XY plane to allow the transit and permanence of people.

In this case, unlike Mies, we pursue the idea of Simplexity, as: from simple parametric rules, we elaborate a complex form.

In addition, in the Tornado is the conceptualization of Solá-Morales (1995) by which the work is self-referential, or it evokes itself and makes explicit its own materiality. However, within the Montaner classification we find ourselves in a situation of the ethics of repetition where there is a repetition of the identical tending to the infinite, using a serial system that eliminates the hierarchy.

The search for almost nothing in this case is NOT of aesthetic order, because it uses simplified design mechanisms. Kolarevic defines this feature as SIMPLEXITY, whereby the complex form is the result of simple design rules. Again, complexity and simplicity cease to be antagonistic and begin to work in harmony in a hybrid consensus already double-handed, whereby the aesthetic complexity, within the precepts of less is more depends on a simplified design.

RULED SURFACE PAVILION

During manufacture, we find a simplification of means, when we use the same slab, and the same logic of fittings, inside and between the frames. In principle each frame would be made by 4 boards of 3 m in length positioned intercalated, and will drew each slab to pass 4 screws at each end. However, by dividing the square to allow a floor (XY plane), a new fitting logic originated and the frame had 5 sides. This new logic of assemble with 5 sides was neither generic nor universal, since in certain moments the assembly logic had to undergo modifications.

We solved this situation by always adopting the frame with 6 sides, an even number (2 of them overlapping, which facilitated the floor execution and fastening), in this way the logic of fittings became universal and we can apply it ad infinitum.

We made five types of fastening throughout the pavilion, three of them to connect the frames together and two to fit the boards into each frame. We establish the connection between frames through single and double spacers, positioned due to the interlayer of the battens; from the point of intersection of slats of different frames; and the locking of the floor, made by infinite screws. We determined the connection inside the frames by the passage of four screws at each end of the battens, which could be lowered (type A screws) or not (type B screws) depending on the existence of conflict with the previous frame.

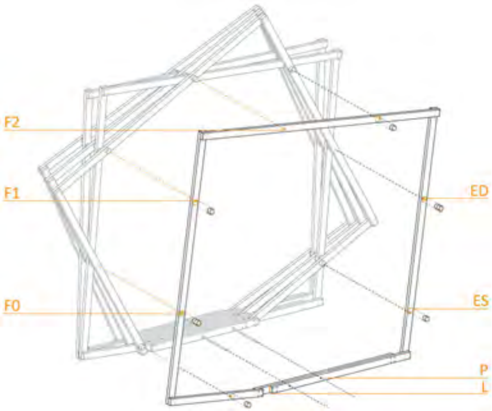


Figure 4
Diagram of connections and fastenings

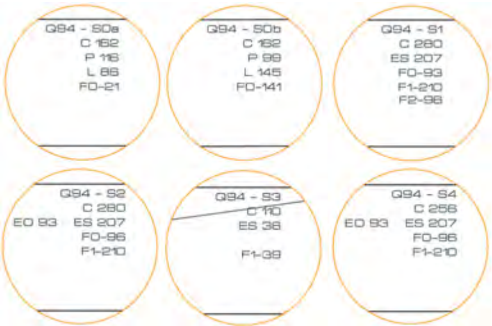


Figure 5
Frame #94 mounting instructions

We thought about the manufacture in a productive logic. As we do not have the Hundeger K2 Robot machine, which would allow the digital manufacture of the slabs, not even a CNC, so we looked for an economy of means. We organized the manufacture and assembly in 9 steps: 1) Marking on the laser machine; 2) Slab marking by hand; 3) Slab cutting; 4) Slab drilling with jigs; 5) Spacers placement; 6) Frames organization; 7) Frames transport; 8) Frames assembly; 9) Frames placement; 10) Pavilion assemblage (Fig. 6).

1 - Marking in the laser machine: due to the intercalated rotation of the frames and their section (with the xy plane) to form the floor, the connection of the floor with the other slabs made different angles, making it difficult to design a common template. Therefore, we used the laser marking to draw in the floor slabs the projection lines of the upper slabs, adjusting the parts position;

2 - Slab handwriting: we created a vocabulary of assembly with all the fixations and information necessary so that the students could draw and mark each slab. Considering always from right to left we marked the following information: the board number (Q), slab name (S0a and S0b for the floor, S1, S2, S3 and S4 for the others), slab length (C), intersection point of slabs of different frames (F0), single spacers center of the front frame (F1), double spacers center of the front frame (F2), projection of the simple and double spacers (ED), axis of the infinite screw of the floor (P), projection lines of floor (L). We gather all this information in a table distributing it to every students group.

We produced this vocabulary during the assembly of mockup models that made possible to understand the rotation and the behavior of the geometry, to verify the importance of each marking and to simulate the assembly of the pavilion, foreseeing possible difficulties

3 - Slabs cut: using the line marked by the students on the slabs (C) cut in the circular saw;

4 - Slabs drilling with jigs: marking the holes (F0, F1, F2, P, screws type A and screws type B) on the table drill;

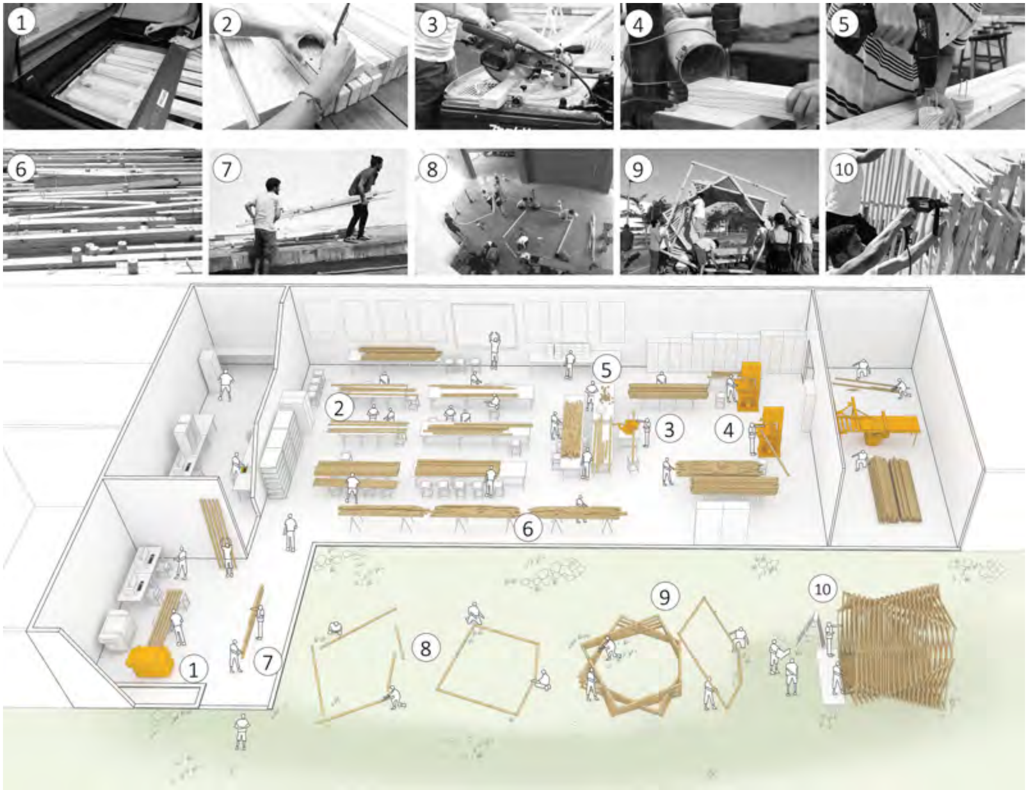
5 - Spacers placement: in the designed projections, we placed the single spacers (ES) and the double spacers (ED);

6 - Frames organization: we grouped the finalized slabs and prepared for transportation;

7 - Transport frames: displacement of all the frames from LAMO to the Technological Park;

8 - Frames Assembly: due to the asymmetry of the pavilion and its manual assembly by different students, it was necessary to produce an assembly notebook. In it, each we drawn each board with all text and marks in the slabs so that the students could follow the map.

Figure 6
Assemblage
diagram



9 - Frames Positioning: we use the F0, F1 and F2 holes to adjust the positioning of each frame with the next frames, performing a geometric triangulation.

10 - Pavilion Assembly: final placement and fastening of the frames.

The pavilion remained for 18 months in the open air, installed in the Technological Park of UFRJ, changing the routines of the place. The intervention meant an ephemeral experience whose objective and subsequent result, besides attending to the task requested, generated knowledge. By bringing together "bottom-up" collective design and construction in a do-it-yourself process, the experience puts both the precepts of tactical urbanism and temporary interventions in practice, as well as to learn the design, fabricate and assemble, in 1:1 scale.

Technology and human expanded abilities

Both in the complicity Mies design and in the simplexity of the Tornado Pavilion we identify the concept of human expanded abilities. Mies in search of an aesthetic of almost nothing and the Tornado with the condition of scarcity of resources and technological limitations. The context made us design and produce considering the human expanded abilities that in both cases unfolds creative solutions.

Still in the context of complexity in architecture, post-Venturi, different areas of Design Think-

Figure 7
Tornado inner vortex, photo. Protection, dynamic shade and breeze. Photo Stefan Kasmanhuber

ing and Design Cognition, rethought design complexity starting with the design concept as an Artificial Science (Simon, 1969). This idea gained new support with the reformulation of the generative systems and the computational tools and processes that enable a synthetic evolution of the project, generating new species and families of solutions. In this sense, research goes in the direction of Design as a complex, comprehensive and innovative activity capable of contributing itself to the "science of complexity". Other sciences face also the same challenge:

"Simplexity may be defined by the combination of simplicity and complexity within the context of a dynamic relationship between means and ends. The quest for simplicity constitutes the basis for all future challenges of organic synthesis: diversity, selectivity, green chemistry, and beauty. Due to the infinity of structures, i.e. properties, that has to be discovered, the focus of synthetic research is shifting gradually from target-oriented synthesis to diversity-oriented synthesis." (Compain, 2004).

This description from organic chemistry can summarize the SIMPLEXITY of the Tornado Pavilion approach. That is also focused on the idea of diversity-oriented synthesis, which goes in the direction of "human expanded abilities" that go against the idea, somehow dominant that the advance of technique per si is a convergent and unidirectional advance. On the contrary, we encourage considering various techniques - disagreeing with the dominant image of unidirectional progress, of an artificial intelligence without context - but rather lead considering

Figure 8
Tornado pavilion
and the group
swarm. Photos
Stefan
Kasmanhuber

the advances to include the human and cultural context in the technical evolution (Henriques, 2016).

In this sense, the Tornado is a simplexity crafted that results from a bottom-up process of a collective, a group of laboratories, and a swarm of motivated, technology-enhancing students. That is, instead of thinking only of augmented technology - for example, by completing the human vision with augmented reality - we present the counterpoint, which is technology augmented by human bottom-up action. In the context of technological shortage, this alternative is a synonym of creativity and overcoming. In this sense, we emphasize the importance of assigning a meaning to the technology that locates it. In the above context of "economy of necessity", we are the robots of this swarm. Give meaning to technology and its practical application, it is undoubtedly a necessity, given the extensive disruptive advance of the fourth industrial revolution.

TECHNICAL CREDITS

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Weaving physical-digital networks:

Brazil-Germany integration experience

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The idea of a network weaved this project in a conceptual as well as in a physical way. A network in the sense of an intangible connection between people, and a network in the sense of a materiality, woven to constitute the skin of a building according to different techniques associated with the ancient culture of covering to provide shelter. We seek to integrate old cultural identities with new digital methods. In the time of the fourth industrial revolution, we might think about a network as something fully accomplished, as if the availability of an internet connection was synonymous with effective communication. In our methodology, we face network challenges at the intersection of human communication and the physical and material domains. The challenge is to discover what to exchange and how to do so. Through the Brazilian-German program `Connect', we tested our research in two practical workshops in two continents. The result suggests that is possible to weave a network incorporating local building traditions and analogue and digital processes of form-finding. The report describes our findings and shares critical reflections opening future research possibilities.

Keywords: *Network, Brazilian-German, Traditional construction, Gridshell, OCA, analogue-digital*

RESEARCH CONTEXT

The fourth industrial revolution is about to bring profound changes in building technology, challenging a re-thinking of local building traditions and associated cultural identities. Schwab (2018) highlights the relevance of collaborative networks to find meaning and purpose in technology. Our Research addresses a local/global gap bridging local building technologies with algorithmic design and digital evaluation. It relies on collaboration to integrate technical and cultural knowledge to find innovative design solutions.

The Research started at a bilateral scientific Conference, where different fields of research, I.e. Sustainable water management, sensor automation technology and digital fabrication for building construction were brought into contact. The conference was part of a meeting organized by Gabriela Celani and Olfa Kanoun at the UNICAMP in Campinas in 2016 (Celani, and Kanoun 2017). The authors presented their research to an audience from different scientific fields during the conference (Henriques, 2017). The first two authors of the paper saw an opportunity to establish a collaboration to combine their research connecting traditional structures and digital building techniques. In South America, there are previous references of the combination of local tradition with new technology as Sperling (2015), and Herrera (2016). Additionally, the collaboration intended to weave a network in two ways:

Firstly, to establish a network to connect people with different cultural backgrounds and practices to incorporate different traditions with current tools in architecture. How to establish a network, what aspects are valuable, how to benefit from the exchange? In the information network it is decisive to reflect about what information can feed the network and how. The scientific exchange triggered the idea to establish a partnership between the two countries; the dialogue would complement our individual ideas and could result in a joint vision.

The second aspect of the network is the physical weaving of material. Based on initial research we decided to re-interpret the construction of a gridshell, a construction principle that has a tradition in Germany - and the OCA, a Brazilian indigenous tradition. We proposed to combine aspects of local traditions between the partner's countries, testing the implementation in a different context. What can Germans learn from Brazil and Brazilians from Germany? How can we cross-fertilise traditional construction principles? How do we join material / physical practices and form-finding with new tools?

Supported by the Alexander-von-Humboldt Foundation - whom we thank for their generous support - the authors established a collaboration between Universities, industries and professional practice. Our proposal suggested that each partner would visit the other, bringing a traditional technique to test in the foreign context using new technologies. The paper describes this experience in five steps:

1. The exchange program and preparation of activities;
2. The first workshop - "Tropical Gridshell experience" and its results
3. The preparation for the second workshop;
4. The second workshop "OCA Traditional Brazilian Construction reinvented" and its results;
5. Synthesis of the results of both workshops and future research potential.

RESEARCH AND PREPARATION FOR THE FIRST WORKSHOP

At the scientific meeting, choosing a partner was somewhat like a speed dating. The partners did not know each other before. They get familiar with each other´s research at the presentations and the social meetings at the conference. In a scientific universe, issues of affinity and compatibility also inform the decision regarding collaborations. Nonverbal and intuitive criteria also influenced the formation of the partnership, which we started with communicating from the distance.

After the conference, the partners discussed how to collaborate and analysed different possibilities of traditional German techniques to develop during a workshop in Brazil. They found potential in the analogue construction technique of gridshells, which we could explore, with the help of digital technologies. Gridshell structures, first used by Shukhov in 1896 (Chilton, 2016), are lightweight constructions that use a low-ratio of material/weight and bare the potential for re-use in a circular economy. We examined in detail the gridshell applied by Frei Otto for the Mannheim Multihalle pavilion. During conversations, we decided to combine the German technique with bamboo as an abundant material in Brazil. Bamboo is a fast-growing material that is light and very resistant but despite its properties rarely used in construction in Brasil. The use of Bamboo is not part of the University program and students do not re-

Figure 1
Tropical Gridshell Experience, workshop at Rio de Janeiro Federal University, March 2018. Trefoil Pavilion, a parabolic hyperboloid gridshell, constructed in bamboo.

ceive a formal education. Therefore, we had to start our own research regarding bamboo properties, processes and suppliers. We looked for a local architect experienced in traditional building using bamboo and an advanced engineer that could use structural programming.

WORKSHOP TROPICAL-GRIDSHELL

The Workshop generated interest from students, teachers and professionals from different states in Brazil and Argentina. We select 14 participants balancing their interests, origin, knowledge and digital experience. The Workshop started with lectures introducing gridshells, explaining the design challenge and methodology. We had lectures from Celina Llerena (Ebiobambu), the bamboo specialist and Felipe

Tavares (UFBA) a structural engineer, so both also guided project development.

The introduction focused on gridshell construction and form-finding techniques. The reference was the Mannheim Multihalle (Frei Otto, 1975) with 85m span, 7400m2 roof area, half-meter thickness and a ratio of span to shell thickness thinner than eggshell. Gridshells are three-dimensional self-supporting structures based on their geometry. The grid patterns replace a homogeneous distribution of material in shell constructions resulting in a "gridshell". We examined the construction process, starting with a flat layout of grids, the design of joins and other details and launched a design challenge. The participants formed five groups of three people each. Each group developed a proposal. All together, we developed and constructed the most suitable one.

The challenge was to design a shelter in bamboo, 1:1 on the University grounds, inspired by the gridshell technique, with special attention to the articulation of geometry/technique/material. We suggested possible sites outside or inside the FAU-UFRJ University Building. The site for the project could take up different shapes according to the project design, a polygon, circles or irregular shapes but had to have a maximum diameter of 10m. Each project should define a shelter, referring to a grid or tessellation, defining the geometry of cells and their connections type. Based on previous studies and budget experiences we selected bendable bamboo slats to enable free-curved forms, acquiring 200 slats, 4m x 4cm with 4mm thickness (average). The consulting architect trained in traditional bamboo techniques was astonished we did not know the exact material number and form at the beginning - we told her about algorithmic design and form-finding techniques to apply in the process.

The act of weaving proceeds human constructions in the nest-like constructions of birds or other animals. Associated with the idea of using a grid is the idea of surface tessellation. Both concepts are associated with the act of binding materials using a material pattern. Binding is also present in the ancient crafts as stonemasons, carpentry, weaving or metalsmiths constituting what Semper claims as archetypes of the innate human building culture (Semper, 2004). The repetition of cells creates different patterns - regular, semi-regular, periodic, aperiodic or non-periodic. The tessellation pattern changes according to the cell´s material and geometry, i.e. squares, triangles, hexagons, or others. Gridshells employ flexible rectangular grids that are associated with a specific behaviour of the grid, that starts flat in the ground and can acquires freeform surfaces.

In respect to gridshells, we identified three relevant factors to define the final design: the global geometry of the proposal, which is defined by the external shape of the proposal, the local geometry that is the type of local divisions or cells. Finally, the type of local articulation or nodes relating global and local geometry. The configuration of the nodes, the material and the cell´s disposition affects the global geometry. The material bamboo was an unknown material for most of the participants. Thus during the workshop we stimulated hands-on empirical testing to predict behaviour besides the use of digital models using visual programming (Grasshopper) and load simulations (Karamba).

TROPICAL-GRIDSHELL RESULTS

Over the course of five days, five groups with mixed abilities developed a proposal through physical and digital models experiencing form-finding in a mixed cycle, digital-analogue. Participants presented unusual gridshell proposals coordinating geometry-structure-material - the entire group developed and built the selected gridshell solution.

We built a 'Trefoil Pavilion´ in the entrance lobby of the FAU-UFRJ University, a paraboloid-hyperbolic gridshell 5 x 5 x 5m exploring form through tension and compression. The folding and unfolding process stimulated participants' geometric and material thinking and the ideas of structural assemblage and erection. The material bamboo proved to be a real challenge even after the try-out of a dozen physical models in different scales and their digital evaluation. We assembled the gridshell flat on the ground and then lifted it with the help of temporary support structures. However, the bamboo structure challenged our predictions and the digital simulation. We had to keep part of the support structure to avoid the gridshell to collapse. Based on this failure, we started a partnership with the civil engineering department to deepen our knowledge about the material and its behaviour. This led to the development a new solution to remake the trefoil installation. We understood that bamboo is as a complex material that even with empirical testing through implicit knowledge and digital evaluation might not be as appropriate for gridshells as materials with more predictable behaviour.

Results discussion. In the development of their design proposals, it proved to be difficult for the participants to resort to form-finding. Although they had an intuition on how to handle and to bind bamboo elements, and despite some experience in modelling, they generally had difficulties to tesselate or divide surfaces and establishing a part-whole relationship, both in digital and in material models. It turned out that the majority of the proposals started from a priori forms. The attempts to adopt these for a gridshell resulted in some cases in polygonal meshes of planar surfaces that were too rigid, difficult to assemble and structurally not gridshells. Finally, three groups adapted flexible grids with different degrees of success. The grids tested were periodic or semi-regular, quadrangular (diagrid), triangular, and hexagonal. The grid cell was primarily obtained from a surface, and the geometry of the cells affected the type of structures proposed. Many structures had rigid connections, few presented flexible connections, which are necessary to employ the idea of assembly used in gridshells. The material applied for the models used for testing was initially paper and cardboard, then strips of wood, wire and rope. It was only when the final construction was selected that the bamboo connections were more actively tested, as the connections in the previous phase were more dependent of the grid type and of cells geometry.

Reflecting on the methodology, we can approach design based on the idea of form-making or form-finding, in the first process, form or global geometry is defined first, in the second local geometric behaviour defines the final form; during the project these two processes can be combined. Participants explored an abstract definition of grid and of tested different combinations to develop their structures. We introduced the participants to the idea of form-finding by physical and geometric behaviour of the material and through computational simulation with the software Karamba. For the participants of the first workshop in Brasil the idea of a gridshell was something new. At first, they choose different geometries thinking about the global form and only then looked into options for cell division. Thus, they imposed a structure to a form, which represents the inverse reasoning. Something similar occurred with the structural simulation, due to their limited experience and the urge to define the global form, the participants used digital simulation only in a later stage of their design.

Reflecting about the difficulties of using form-finding, we can interpret this as cultural difference, which would suggest the application of a more didactic methodology, starting with a deeper understanding of an existing model and the introduction of several ways to model and build a grid. Especially the reference to the legacy of Frei Otto (Nerdinger, 2005) is more known in Germany and we would need to address in detail to overcome the different cultural backgrounds.

Our conclusion is that the explanation for both cross-connected groups, should explicitly include the participants cultural background.

PREPARATION SECOND WORKSHOP

After the conclusion of the workshop in Rio, our interest in the use of bamboo increased, but we also realised that due to the complex nature of the material the technique of how to use it structurally needed a more solid preparation. Therefore, we formed a study group at UFRJ, which conducted regular meetings. We thought of this as a research and a preparation for the upcoming workshop in Germany. As topic for the second workshop, we selected the OCA, indigenous traditional constructions that were popular in Brasil, although most of the participants of the group had never visited one or had any idea about the construction. The material we collected included drawings, but was not sufficient to construct an OCA (among other books by Lengen 2013, Weimer 2012, Montezuma, 2002).

The material about the OCA is vast but disperse, which led us to organize our search in respect to understanding what the more important aspects. The OCA traditional indigenous constructions are foreign even to Brazilians, so we decided to address the following topics working in groups:

The OCA house typology and its urban organization: we identified and systematized a geometric vocabulary with visual programming as found in vernacular indigenous constructions. We defined plans, sections and structure as focal points. Defining primitive and attribute values generated a range or spatial solutions. Plans were circular, elliptical, semi-elliptical, rectangular and polygonal; Vertical sections triangular, ogival and semi-circular. The support structures applied were central pillars without perimeter columns, with singular perimeter columns and two or more rows of perimeter columns. Structures with more than one central pillar had rectangular, polygonal or semi-elliptic plants. To erect these shapes structure included a table made of pillar-beam supporting the shell cover. House unity changed according to tribe and region in Brazil. We found three urban organizations: the horseshoe, circular or single houses.

Building Technologies: we studied foundations (above ground, buried, semi-buried), materials, connections (longitudinal, transversal, others) and enclosures (metal, wood, grout, straw, canvas) and synthesized the examples in an overview table. A visual study using sketches to document the connections and the construction assembly applied in different cultures (Horning, 2009).

Structural Systems can be classified in 7 types according to Engel (2015). We found that the OCA uses four of them: Form Active, Vector Active, Section Active and Surface Active Structures. We tried to adapt an OCA to other structural types seeking to define new possibilities. We collected examples of around 40 bamboo pavilions and analysed them according to the previous subjects. This intend was to combined traditional-contemporary solutions, to understand differences, challenges and opportunities.

We found that OCAs often had an internal table structure, which supports the outer covering, and that the table supports the outer curved shell. One of the challenges was how to eliminate the table, creating self-supporting surfaces - that could act like a real shell in the structural sense - such as gridshells - or how to hybridize them, to obtain a more integral construction system.

After completing these studies, we tested the construction of OCAs with physical models, but there was a short time before the workshop to develop these models. Looking at this aspect now, an in-depth study of grid models would have been very useful to support the development of an OCA based structure and would have increased the conceptual clarity of the three-dimensional elements of the structure.

Another result from the preparatory research was the material to use for the workshop in Germany. Originally, we envisioned to use bamboo as studied in relationship with the OCAs. While only some of the original constructions employ bamboo we were interested to continue with the material bamboo after the first workshop. In the process of preparation, we found that to work with bamboo in Germany, we would need to import the material from another continent, which proved not to be feasible. Therefore, we considered using wooden slats. Economic and easily available elements are 4x4 cm slats with a length of 6m. They are frequently used in roof constructions in Germany, but with the experience we had exploring the design of the OCAs we realised that this would limit the geometry to stiff wood, or pitch-roof like

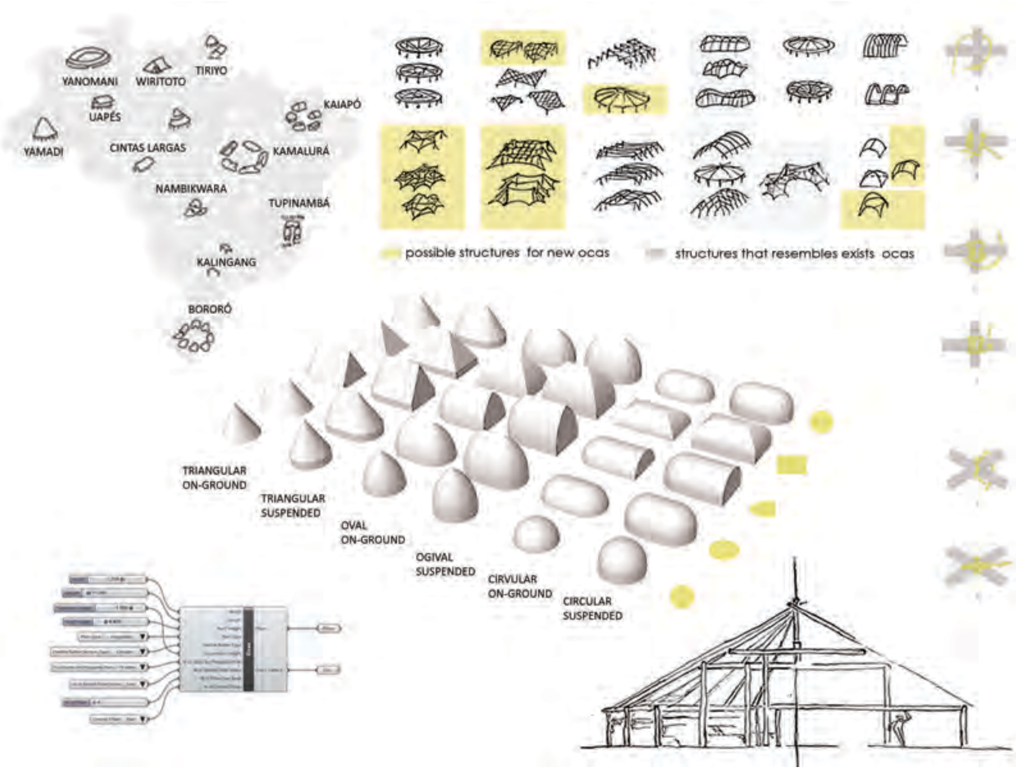

Figure 2
OCA preparatory research: urban settlement typologies of indigenous camps; structural types used in OCA; Bamboo constructive tiding studies, cross-section of traditional example. Parametric model developed combining the type of horizontal and vertical sections that define an OCA grammar. The grammar documents existing solutions so we can identify complementary solutions and future improvements. Drawing by Amanda Ribeiro and Christian Jesus.

structures. We considered sliding the slabs in halves, but the nodes of the pinewood affect the homogeneity resistance and might break if we apply too much bending in the slat. Finally, we found a suitable substitute, which we would latter call the German bamboo in the application of PVC pipes used for electricity installations. They are light, resistant, equipped with connectors, are cheap and easily bend. Therefore, facing a difficulty we had jointly discovered a creative solution to come closer to our goal.

WORKSHOP OCA

The challenge of the workshop was to connect the new students form the academy in Stuttgart to a group of Brazilian students that participated in the preparatory research and had come to the workshop with DAAD support. We had to introduce the new participants to the concept of an OCA. Following long discussion about what to present from the research, we introduced operative concepts of the OCA as typologies, building systems, materials and structure. However, some of the Brazilian students argued that it was far more than that this, as it forms part of a nomadic and ecologic way of living and a cultural expression and art. We solved this difficulty presenting the OCA in a more open concept as a shelter and construction, so participants from diverse cultural backgrounds could appropriate it.

During the introduction, we presented the preparatory research. An OCA possesses an inner nature of protection and establishes a social and spatial relation with the space it organizes. We presented diverse types of group organization of the OCA buildings. As in the previous workshop, we introduced some constraints and remembered participants to articulate geometry / technique / material. We organised complementary lectures about digital fabrication, simulation and calculation, by Tobias Schwinn (ICD), Arnold Walz (Design to Production) and Thomaz Vieira (Detmold) who later on supported the workshop with the application of digital form finding in Karamba.

OCA RESULTS

We conducted the workshop with participants from Brazil and Germany from diverse study programmes and experiences. During five days, four groups developed proposals with the help of several physical and digital models. This continued the first workshop form-finding process. Several proposals articulated the combination of geometry/structure/material successfully.

The participants incorporated the idea of shelter relating an inner and outer space. The constructive process of the OCA structure was not as defined as the Gridshell. This difference has two reasons: an OCA constitutes a different system and we might need extensive research to understand the OCA construction techniques in depth. Especially because the proposal set out to avoid a table system to support the OCA. The participants developed revolution structures that followed rail curves with free forms; some proposals incorporated the idea of bending tubes to attain curved surfaces, and others thought to use the tubes in combination with wooden slabs. Defined by the overall form there was a challenge to think how to connect the portal frames that in the majority of cases would require the development of three-dimensional complex joints. The selected form to construct is based on a set of petals that are arranged in an array, creating a space of relationships between the exterior and the interior where a protected patio is created, which would be the place where the Indian tribe would gather, to light the fire.

The built pavilion yields a new typology combining process, techniques and cultural experiences.

The pavilion is a group of five rotational “petals”, organizing a central void for the fireplace surrounded by benches. The rotation and intersection of the petals creates niches in-between. The petals size decreases to the center, inviting to enter and sit. Each petal is a separated grid with PVC bended pipes connected with a standard male-female plumbing. We crossed the main bended arches with complementary smaller elements of bended tubes in the other direction to create concave-convex double-curved fittings that we fixed with cable-ties, resulting in a ruled double-curved grid. We carved wooden pegs and stacked them in the ground. We slot the pipes arches in the wood stacks. We made use of a traditional German carpenter measure tool to crave the different angles. We tested covering the petals with plastic film to increase the OCA protection effect.

COMPLEMENTARY WORK

To foster collaboration, and get in touch with state of the art, technologies we visited different universities and research centers, with meetings and lectures. We visit UDK Berlin University Arts, Prof. Norbert Palz/Sven Pfeiffer; ICD Universität Stuttgart, Prof. Achim Menges, Tobias Schwinn; ABK Stuttgart. We visited Franken Architekten GmbH, Frankfurt; LAVA Offices Stuttgart, Berlin; NOWlab/BigRep Jörg Petri, Berlin; in Stuttgart: Design to Production, ILEK Lightweight Institute Frei Otto, and Mercedes-Benz Museum. Professors visit places in Frankfurt and Berlin, and then the all the group visit places in Stuttgart.

DISCUSSION

The purpose of the collaboration was to exchange knowledge in the fields of technical, cultural and human aspects. Learning by doing with others in a combined empirical-technological process. On one hand, the context of the Brazilian Lab ‘LAMO´´ with

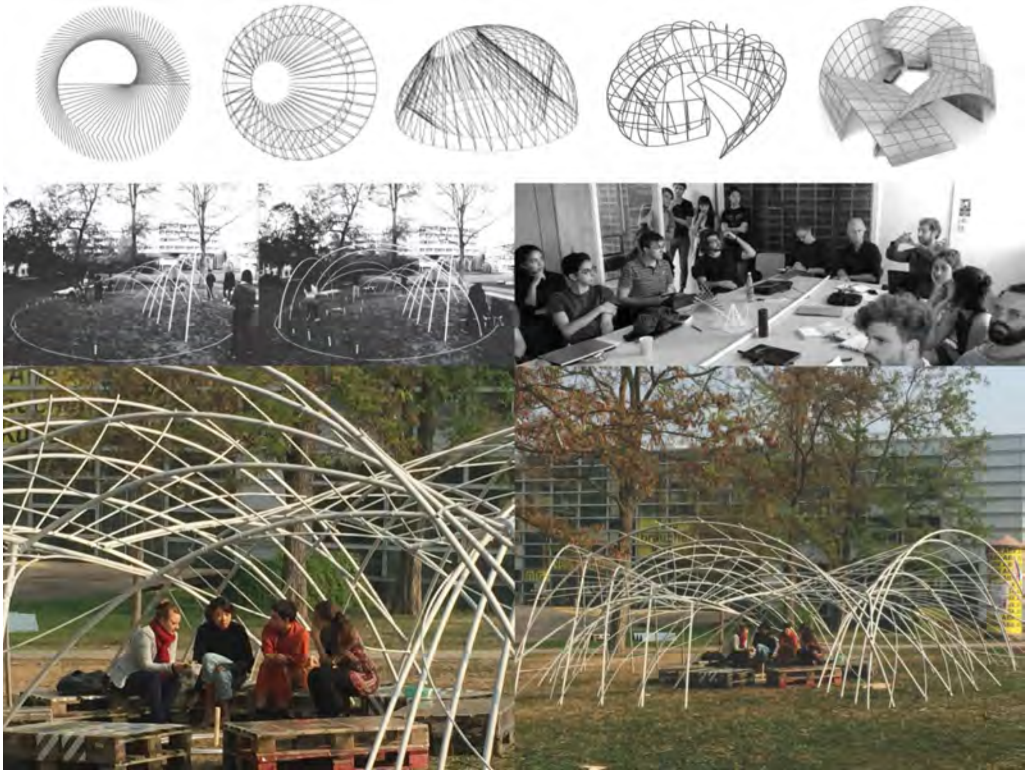

Figure 3
Workshop OCA traditional Brazilian Construction reinvented, October 2018 at ABK-Stuttgart- Solutions developed during the workshop, construction process and the final pavilion that interlaces bended-pipes to form a ruled-grids structure with a central gathering void.

its highly motivated group used to an informal working process stimulating creativity. Students improvising to overcome obstacles, making intuitive and empiric use of material and techniques. On the other hand, the German Lab very well equipped with a formal structure, run by experienced professionals, but with limitations to use of the facilities for foreign students and time constraints for the local students during the workshop period. German students used to solve problems interacting with seniors, something new for the Brazilian students.

The structure of the OCA is a vernacular construction that makes the best use of the most abundant material that exists in the place in an expedite construction. It uses a table to support the outer shell. In this sense, it has a different nature from the gridshell that is engineered, in an erudite development, which has no additional support elements as structure. One construction is optimized by the available materials, while the other is optimized in the search for the best structural solution, based on the study of minimal surfaces as found in nature. This does not mean that we cannot combine these two types despite their different natures. We believe that a complete fusion of these two constructions needs further research.

In the first workshop, we built a new type of gridshell with a novel material. We then studied traditional OCA structures with the aim to eliminate the table as a structural support system inspired by the gridshell. During the second Workshop, we developed a new type of structure combining OCA shelter with a gridshell introducing a different material. We do not develop the technical aspect of the construction in depth, as this was not the research focus.

Students remember the workshop for learning multiple factors that affect architecture, how to develop multiple aspects of a design and how to test various design options in a quick way with the help of analogue and digital modelling techniques. Through the research of traditional techniques and materials and their combination with construction elements from a different continent, the project created new ways of connecting people. During the short time of five days each workshop provided a special experience containing discussions, digital simulations, hands-on making and in the end the celebration of the erection of a 1:1 prototype. The high-speed joint development of a piece of architecture by strangers. At the end their eyes blinked, we had fulfilled the purpose of creating multiple networks.

CREDITS

Workshop Tropical Gridshell experience / FAU-UFRJ Rio de Janeiro, March 2018. Coordination: Tobias Wallisser and Gonçalo Castro Henriques; workshop support by Daniel Lenz, Felipe Tavares. Lectures: Tobias Wallisser (ABK/LAVA), Celina Llerena (Ebiobambu), Felipe Tavares (UFBA). Participants: Amanda Ribeiro, Christian Jesus, Cristian Fagundes, Erick Maiworm, Francesco Milano, Isadora Tebaldi, Karen Antorveza, Leonardo Pate, Mariana Chalhub, Nicolle Prado, Pedro Teixeira, Pedro Engel, Rafaela Engler, Sol Ztt, Thatilane Loureiro, Thomas Anjos.

Workshop OCA Traditional Brazilian Construction Reinvented / ABK Stuttgart, October 2018. Coordination: Goncalo Castro Henriques and Tobias Wallisser; support by Daniel Lenz, Sebastian Schott and Arnold Walz (Design to Production). Lectures: Gonçalo Castro Henriques (UFRJ, LAMO), Tobias Schwinn (ICD), Thomaz Vieira (Detmold). Brazilian Participants: Adriane Ossaille, Amanda Ribeiro, Christian Jesus, Erick Maiworm, Isadora Tebaldi, Leonardo Pate, Rafaela Engler and Ronaldo Lee. Collaborators OCA research: Lais Kaori, Pedro Teixeira and Thatilane Loureiro. German participants ABK Stuttgart: Andreas Klatzka, Felix Joachim, Frida Ruppe, Hari Wolfer, Lu Chéng, Isabella Altemani, Tobias Haas.

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Towards an Architecture of Collaborative Objects

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Towards an Architecture of Collaborative Objects, explores the potential of playing with Collaborative Objects in real, augmented and mixed realities. A multi-player game platform App: VoxelCO, developed by the author, provides a speculative playground to research, the interaction with objects, things and people, as well as provokes new opportunities to engage deeply with its content and context. Furthermore, VoxelCO, reveals new modes of participation, to design and collaborate in real-time with augmented reality, using millennial tools: mobile devices. A case study project, the VoxelStage, offered an opportunity to apply VoxelCO to design a stage together with a group of students. To merge the collaboratively aggregated virtual objects of VoxelCO with reality, real WireCubes were augmented and assembled, proposing an architecture of socially augmented fuzzy formations.

Keywords: *Collaborative Objects, Augmented Reality, Realtime, Fuzzy, Play*

Introduction to Collaborative Objects

"Technology has already transformed our lives, bringing together people, ideas, and information in unimaginable ways. We're hard at work in a new technological chapter that connects the digital world with reality"(Niantic 2019), a statement by Niantic, a company that recently blurred the boundary of what is digital or real on a massive scale. The expertise of Niantic, developed among others from being involved in creating project Keyhole, which later evolved to Google Earth. Further on they developed their first geo-location based mobile game Ingress which allowed the users to claim virtual territories in the real world as well as enabled them to create content, documenting and mapping the real world and merging it with the virtual game. Building up on the collected data of Ingress, in 2016, Pokemon GO launched like a rocket, leading in the app charts for the following years. Besides the geo-location implemented in the game, advanced social concepts to collaborate, trade and raid, as well as augmented reality were introduced, mixing the realities of the game content. As Mario Carpo suggests, *"Every technology is a social construction: innovation only occurs when technical supply matches cultural demand, and when a new technology and new social practices are congruent within the same techno-social feedback loop."(Carpo 2017, p.159)*

I argue that social network platforms, enabling interaction with digital or real content, objects and people, as well as a technology like augmented reality allow for new forms of collaboration in architecture to emerge. It's time for architecture to investigate those *'unimaginable ways'* to bring together people, ideas, information and objects. Therefore Collaborative Objects are introduced as conceptual

Figure 1
Millennial Tools to play VoxelCO at Augmented Playground

framework for the interaction between human to object, as well as object to object, in real or virtual environments and playgrounds towards an architecture of socially augmented fuzzy formations.

Being Collaborative

When Nicholas Negroponte portrayed our near future as, *"The middle ground between work and play will be enlarged dramatically. The crisp line between love and duty will blur by virtue of a common denominator - being digital"(Negroponte 1996, p.220)*, we have to admit that we are not yet 'digital', but I would suggest we are close to 'Being Collaborative'. Enabled by the Internet and diffuse mobile devices, social network platforms and other forms of peer to peer production, together, empowered a culture of collaboration. As we recently learned again with Pokemon GO, a massively multi-player online game (MMO), *"play is the central element through which cultures enact itself."(Bogost 2016, p76)* MMO's enable players to connect to a main server, to get access to the game's digital playground. The server provides what's called a persistent game environment, a mechanism to ensure that the digital world map, all the changes a user makes to it, as well as the progress a player makes, is stored properly. This allows the digital playground to be a collaborative environment where users can interact with each other, with objects and their environment. Furthermore those open world games, with non linear play, enable in-game culture to emerge. Critically regarding contemporary production of architecture, there might be a shift towards social collaboration in the design process, as Jose Sanchez puts forward, from *"growing form and producing differentiation by a omnipresent designer, the democratization of tools and the collaborative commons searches for massive social recombination, allowing differentiation not to be designed but to emerge from the interplay of resources and social innovation."(Sanchez 2014)*

Playing with Collaborative Objects

Galit Ariel, offers some basic principles to explore our current reality:*"We learn about our reality through exploration observation and play." (Ariel 2017, p.170)* Exploration and observation are quite familiar in our reality of efficient architectural design and education, but usually there is not much serious or non-serious

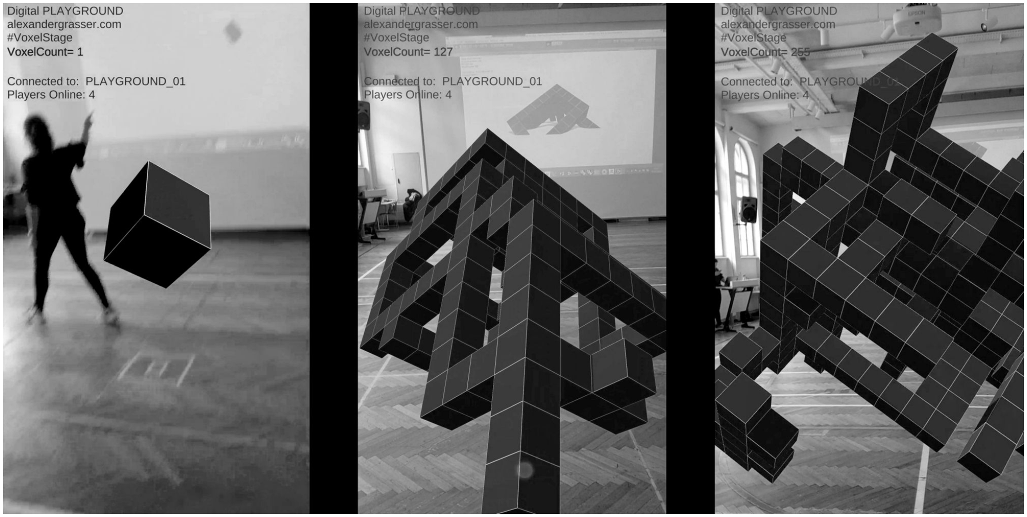


Figure 2
Virtual Voxel-Formations at Augmented Playground, mobile phone gameplay screenrecordings @VoxelCO

play involved. To collaborate and to play with clients, colleagues, students, objects and discrete units offers a huge potential as soon as we look at it, the way Ian Bogost is looking at play:*"Play is in things, not in you."(Bogost 2016, p.91)* To play with Collaborative Objects in real, augmented and mixed realities we need to engage with them deeply until they reveal their capacities, potentials and something new. A familiar platform enabling interaction, collaboration and play: the playground, offers the potential to re-frame architecture in a speculative way. As Ian Bogost mentions *"it's content is real - but the frame of a playground helps make the real world partly fictional. It wraps an imagined boundary around something, allowing us to suspend temporarily our ordinary relationship with it as ground and to see it new as figure."(Bogost 2016, p.87)*

By deliberately working and engaging with objects and things on a playground we might encounter some of their hidden capacities, as Bogost puts it: *"Fun is the feeling of finding something new in a familiar situation."(Bogost 2016, p.6)* Collaborative Objects are trying to find those moments of fun in a familiar architecture.

VoxelCO

To research the potential of engaging with Collaborative Objects, the App 'VoxelCO' was developed by the author. A collaborative multi-player platform, trans-reality game, cross-platform suitable for PC, IOS and Android. VoxelCO is based on a simple game logic of allowing players to place or remove virtual voxels to a persistent game environment. Furthermore VoxelCO allows for collaboratively playing and displaying the interaction with objects in real-time using augmented reality on mobile devices. As described by Galit Ariel: *"As consequence of applying Augmented Reality our physical environment (and reality) would become a Sandbox platform - allowing users to freely manipulate and apply digital content within it."(Ariel 2017, p.125)* , VoxelCo's social augmented reality provides a playground for intensive collaborative interaction with real and virtual content and players. As well as provides a tool to deeply engage with Collaborative Objects. The potential that Negroponte identified in the pixel, *"The real power of the pixel comes from its molecular nature, in that a pixel can be part of anything,"(Negroponte 1996, p.125)* shifts in VoxelCO from 2D to 3D, from pixel to voxel. The voxel, a dis-

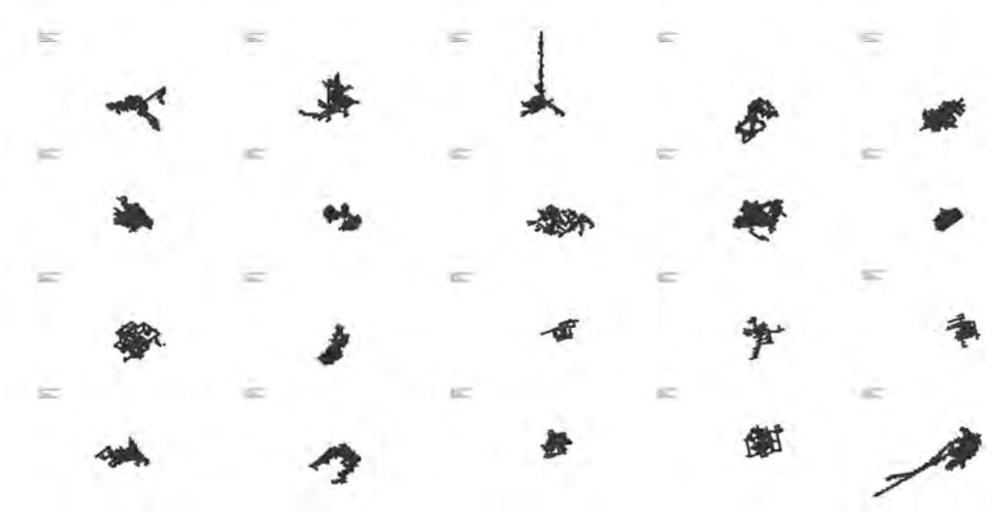


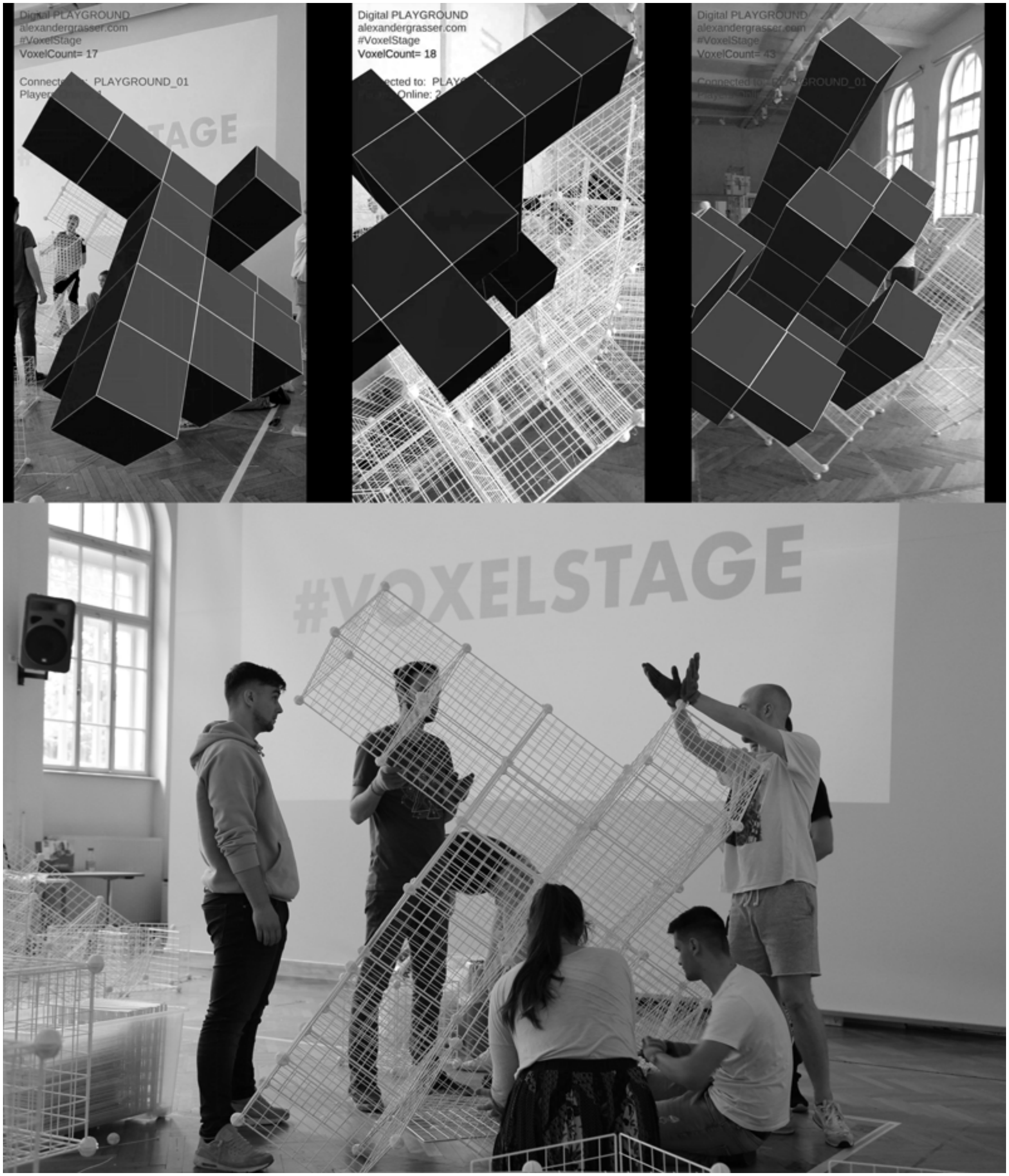
Figure 3
Virtual Voxel-Formations at Digital Playground @VoxelCO

crete unit, or simply the box is a familiar object in architecture to play with, to aggregate socially augmented fuzzy formations.

Collaborative Playgrounds

To play the game, players start the app VoxelCO, choose a player-name, and by pressing 'collaborate' they connect to the server and join a design session 'the digital playground'. At the digital playground, players can always instantiate new voxel by placing them in close proximity of visible faces of other voxels, immediately becoming the owner of that voxel. Players can only destroy their own voxels, but as soon as a player gets offline the ownership of his voxels get transferred to all the other players currently online, allowing them to rearrange or remove those voxels. It is possible for players to re-join a design session. Players can save the current Voxel-Formations, share them, as well as load and animate the instantiation sequence of previously saved Voxel-Formations to further rearrange, add or remove voxels. A game mode challenging ownership as Cathy Casserly wrote, "People used to think of reuse as stealing: today, not letting others use your work can mean irrelevance."(Ratti 2015, p.86) To further open up the collaborative digital design process, the game uses augmented reality to blur the digital and the real. In order to place a new voxel at a desired position, the players have to move around the virtually placed voxels, displayed on their mobile devices. A sense of scale, by interacting locally with parts as well as the whole gets real, as well as reveals the constraints of the game, a limitation of the height of the Voxel- Formation, as you can't place a voxel if you can't see the voxel- surface you want to access. Furthermore social collaboration of real world players gets meta-interactive, as its turn based game design evokes reflection, as Ian Bogost mentions on abstract games, "The player must always intervene to make the next move, offering an opportunity to reflect on the enormity of the task, a requirement of sublimity."(Bogost 2009) The trans-medial fluidity of the collaborative design session becomes visible when a player is leaving the digital playground, but is still visible in the real playground able to reflect, interact and collaborate with the other participating players.

Figure 4
Virtual
Voxel-Formations +
Augmented
WireCube-
Formations at
Augmented
Playground
@VoxelCO



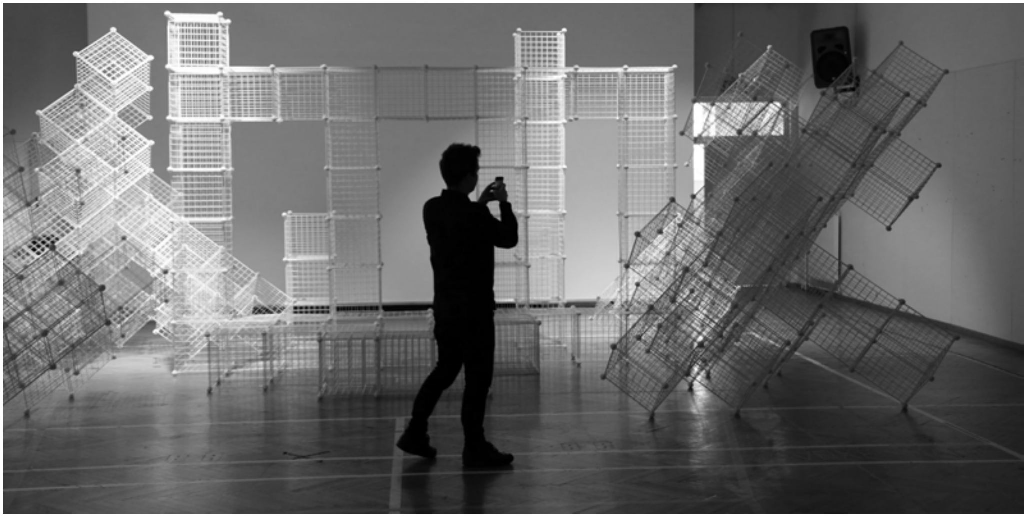
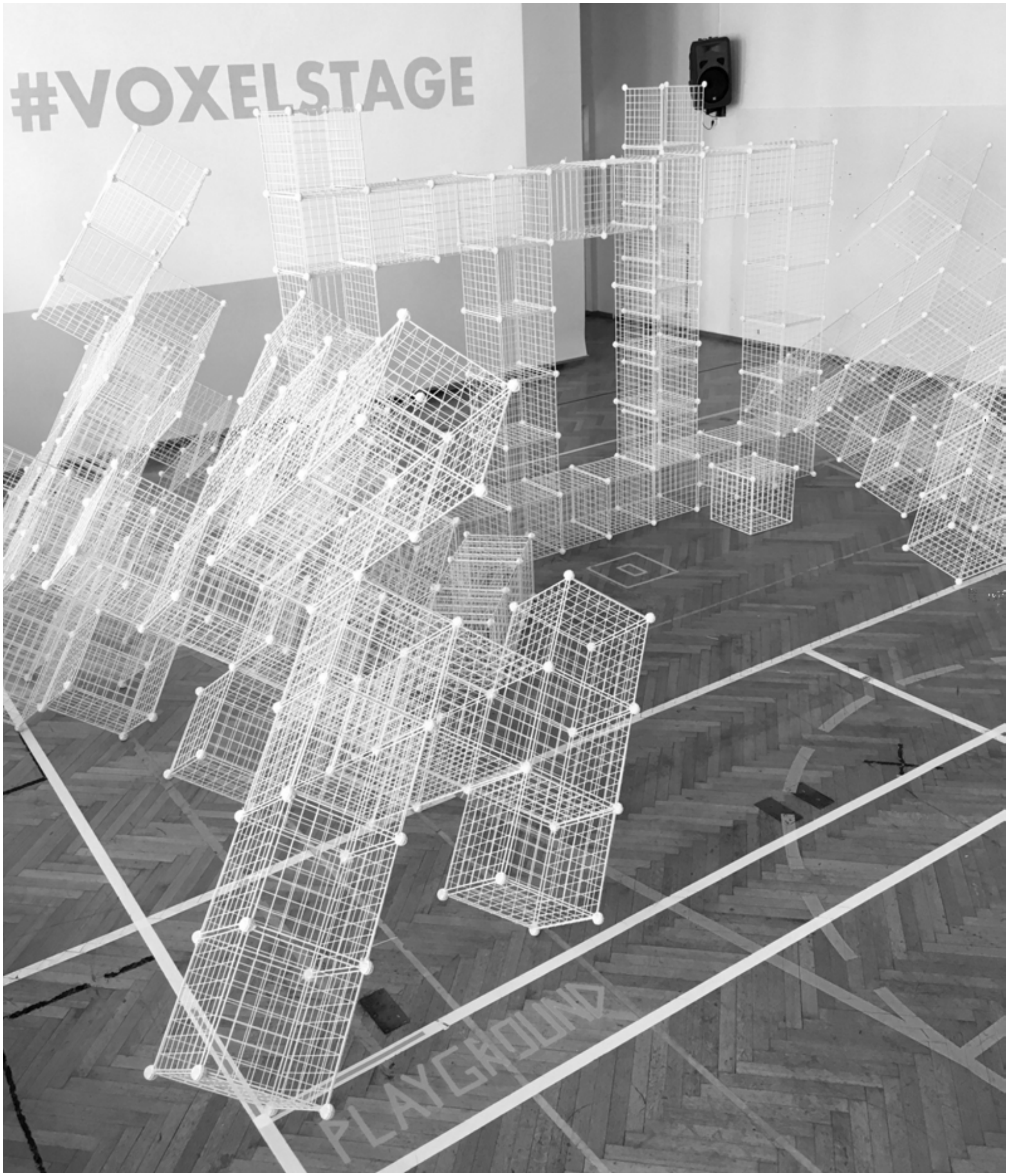


Figure 5
VoxelStage at Augmented Playground

VoxelStage

To apply the research of Collaborative Objects, a five day workshop with 20 bachelor students and the commission to design a modular stage for a festival offered a great opportunity to develop collaboratively a case study project, the 'VoxelStage'. The workshop explored the potential to merge the digital game of VoxelCO with our physical environment, as Carlo Ratti proposed *"The kernel of architecture exists as data, is honed by a distributed sequence of adding and editing, and finally culminates in a physical structure - the execution of code in space."(Ratti 2015, p.109)* The workshop was designed to teach the concept of developing a real-time multi-player platform with it's simple design logic, as well as to teach how to deploy the app on their mobile phones in an efficient way. Focusing on enabling the students to start playing with VoxelCO and to develop collaboratively virtual design proposals for the VoxelStage. Groups of 5 to 20 students designed at the real-time digital playground, as well as at the augmented playground, moving around to add or remove voxels, debating, arguing, designing and instantiating between 100 to 1000 voxels per design session. A Metaverse of Collaborative Objects emerged. To execute the code in space, transferring the virtual VoxelStage to the real, students had to place real voxels, in our case WireCubes(40*40*40 cm) were provided. By using VoxelCO's function to load a instantiation sequence of a Voxel- Formation, loading one voxel after another, augmented reality provided a virtual overlay guiding mechanism to place the Wirecubes in our physical world, accelerating the assembly of stacking and connecting. The design sessions, alternated between playing with and aggregating virtual voxels in augmented reality, testing design options at the augmented playground, as well as analogue design sessions collectively aggregating the WireCubes to test their limits at the real playground. While playing and testing the platform VoxelCO to design the VoxelStage, adaptations and revisions of the application where made if needed. For example, disabling the ability to remove a voxel in design sessions was necessary, as it was sometimes not possible to remove a WireCube easily from a real WireCube- Formation without removing some neighboring WireCubes. Which as a side effect gave the instantiation of the virtual voxels more relevance and value.

Figure 6
VoxelStage



Furthermore, multiple design sessions with different constraints provoked different game strategies and modes of collaboration to emerge. From the fist access to the multi-player digital playground where the students came up immediately with 6000 instantiated virtual voxels, to design sessions with the goal of instantiating 400 virtual voxels, to design Meta-Voxel-Formations of 20-40 virtual voxels as well as to build their related real WireCube- Formations.

VoxelCO framed a playground to mix and blend reality to deeply engage with Collaborative Objects. A collaborative design process similar to what Ian Bogost describes *"Most often, puzzles are entirely conceptual in form, with concreteness a mere accident of presentation."(Bogost 2009)*

Notes on the Metaverse of Collaborative Objects

As the range of skills involved in setting up the game platform, deploying it to the phones, as well as to play the game, to connect the WireCubes and socially collaborate, with the goal of ending up with a sublime VoxelStage, I quote again Nicholas Negroponte describing a child being interviewed during a Lego Mindstorms Hackathon at MIT saying:*"Yes, this is fun, but it's hard fun."(Negroponte 1996, p.196)*, along with a response to the introduction quote by Niantic I reply, as architect, *"We're hard at work in a new technological chapter that connects the digital world with reality."(Niantic 2019)*

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VoxelStage Collaborators: Alexandra Parger (NanaDesign), Anna Brunner (Fifteen Seconds)

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VoxelStage Students: Nadina Bajric, Emir Dostovic, Dijana Imsirovic, Jelena Josic, Larisa Kolasinac, Anela Mikic, Inas Dizarevic, Fabian Jäger, Matea Kelava, Bianka Marjanovic, Sali Ren, Sarah Salkovic, Anela Smajlovoic, Mirna Vujovic, Fabian Rigler, Cornelis Backenköhler

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Computational Design in Distributed Teamwork

Using digital and non-digital tools in architectural design competitions

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This paper reports a case involving computational practices in design process with an aim to understand the role of digital and non-digital tools in the design process. Following an ethnographic approach, we aimed at understanding the nature of the interactions among team participants which are human and non-human in a distributed system. We focused on computational practices in design process and we aimed to understand the role of digital and non-digital tools in the design process. Tools have remarkable role in a distributed system in the sense of propagation of knowledge. It was observed that form exploration by digital tools may not controlled as much as sketching.

Keywords: *Collaboration, Distributed Cognition, Computational Design, Visual Calculation*

INTRODUCTION

Design is a distributed cognitive system consisting of interaction, computation, generation, communication, synthesis, and manipulation of tasks (Lyon, 2005, Lyon, 2011, Cross, 2006) by a series of human and non-human agents. In the architectural design processes, designing and construction stages involve various participants from different disciplines who contribute to solutions to design problems in light of their responsibilities shaped by their areas of expertise. In such a system, one question that stands out relates to the nature of collaboration among participants from different disciplines and with different expertise. According to Cuff (1992), an architect or a designer can have a key role in design decisions but almost every step in practice is associated with collaborative work. Architects can be an expert in many subjects such as space design, aesthetics, site planning, function, structure, mechanical systems, graphic communication, but it is obvious that they need experts from other disciplines (Cuff, 1992). Recently, various digital technologies are used to increase participation and collaboration to increase efficiency in problem solution. The research focuses on architectural practices as a distributed cognitive system to understand the complex project generating mechanisms mentioned above. Analytically, researching architectural project production mechanisms as a system requires a holistic view. The system that comprises humans, objects, and tools can be framed as a distributed cognitive system following the work of Ed Hutchins (Hutchins, 1995). Distributed cognition assumes that any task can be distributed across different parts of a system (Hutchins, 2014). Collaboration, in this framework, involves not only human participants but also other parties such as tools and representations. In this research we have employed the distributed cognition framework in order to account the interactions among human and non-human components of a system.The research focuses on the activities of a team of architects using computational design tools in the design process leading to a proposal for a competition. Within the case the team has employed the computational tools in developing solutions for secondary systems or components, rather than generating the overall form of the design. Given the constraints of the competition program, the computational tools were observed to be instrumental in increasing the number of alternatives, in problem solution, and in streamlining time-consuming tasks. The paper tries to explore the mechanisms, online and offline, in developing particular solutions which required a level of coordination between participants of the cognitive system. The next section introduces the idea of distributed cognition in the design context we have observed through ethnographic field methods.

DISTRIBUTED COGNITION

People interact with other people, artifacts, technologies, tools, surfaces, and the things that are represented to the others. People also interact with their environments as being 'embedded' to coordinate their internal cognitive tasks with external tools (Kirsh, 2008). People's cognitive activities results from interactions with external cognitive artifacts and with other people's activities in a task that are determined by social and cultural contexts and physical environment that they are positioned in (Suchman, 1987, Hutchins, 1995). Distributed cognition discovers and explains the principles of coordination, externalization, representation, and interaction (Hutchins, 1995). Distributed cognition frames the cognitive process of human and non-human mechanisms that are participate in a task (Hutchins, 2004). Hutchins (1995a) describes computation observed in the activity of the larger system as "computation realized through the creation, transformation, and propagation of representational states" . According to Hutchins (1995), to understand navigation system, we need to understand information processing system within the organization. In this research, we assume that an architectural design team as a system consists of human and non-human participants. Each of the participants contribute to the system and information is propagated between them. We, now, turn our attention to computing practices in the distributed cognitive system observed in this research.

COMPUTATIONAL DESIGN AND VISUAL CALCULATION

It is claimed that the computational thinking changes the way we think (Bundy, 2007). Computation has always been a part of design (Carpo, 2011), however the adaptation of computational design tools has been a relatively new phenomenon. Design always proceeds in the form of a calculation and can be explained with algorithms and computation (Stiny and Gün, 2012, Pask, 1963). Computations involve numbers as well as shapes. Stiny (2006) states that design and calculating is equal and puts forward that in designing designers "are actually calculating in a visual sort of way, whether you know or not, and the real central issue, at least for most of my work, is to try to figure out how calculating includes design" (Stiny and Gün, 2012). Visualizing design ideas, according to Stiny (2006), is a form of calculation through which ideas are represented and tested. According to Stiny (2012), designer thinks with eye and seeing is the most interesting part of the design process. The formulation offered by Stiny is a form of "reflective practice"; an interactional process in design which follows "seeing-drawing-seeing" defined by Schön (1991), designer reads the situation and interprets again while drawing in the design process. Schön emphasizes sketching as a valuable tool for representation and exploration (Schön, 1991). Concerning the research presented here, the emerging question whether or not the tools employed in computational design replaces the conventional sketching practices involving representation and exploration. Stiny (2006) states that visual rules are also used for calculation for formal operations in design. However, designers generally unaware of possible alternatives of their actions while designing (Visser, 2010). Within this perspective, it is a valuable research question to think about the relationship between sketching activity and computing activity.

METHODS AND THE CASES

The research is a qualitative study which consists of ethnographic observations of a professional architectural team. The selected office uses digital technology and computing in their design process. Data collection included the following stages. First, we conducted in-situ observations of two competition projects from beginning to end for a month. Ethnographic observations were used to understand groups and people in their everyday professional lives (Emerson et al., 1995). Second, we conducted semi-structured interviews with significant team participants. The semi-structured interviews were face-to-face to provide a way to explore feelings, opinions and behaviors (Sommer and Sommer, 1997). The interviews helped in figuring out the teams' information processing systems in the process, in understanding the communication strategies and knowledge representation techniques of the teams, and in providing a lens to understand participants' descriptions of a situation. Data analysis included the following three phases: description, analysis, and interpretation of culture-sharing group (Creswell, 2007). In the first phase, all the data has been indexed in a time line to understand the phases of the team's design process. Data types have been coded in the time line as sketch, photograph, field notes, meeting minutes, video records, audio records, screenshots, and e-mails. Grounded theory involves analytic attention and provides a procedure for developing categories of information which is called open coding (Strauss and Corbin, 1990). In the open coding phase, the text is examined and emergent categories are identified by the researcher. Categories that are listed according to selected phenomena, are interconnected as axial coding to create categories. Creating relationships between the categories and building a 'story' which connects categories is called as selective coding (Strauss and Corbin, 1990).In this research, the focused team consisted of one architect team leader (TL), two architect job captains (JC1, JC2), and seven intern architects. The team participated in two different architectural competitions at the same time. Competition A was about a youth center design, Competition B was about a municipal service building. In the team, one job captain (JC2) and one intern (IA1) were more interested and capable of computational design tools then the other participants.

FORM EXPLORATION BY TOOLS

Computational design tools are seen as expediting the design problem solving, especially the tools enable searching a wide range of solutions, and visualizing the data to establish collaboration among participants (Olsen and Namara, 2014). Exploration of the form was carried out by the job captain and the team leader in the design process of the competition A's meetings. The competitive nature of the design process has adapted all the team participants' motivation about idea generation. In the meetings of the competition A, the team developed sets of rules in the sense of settlement on the project site, design and size of the lodge units that were given in the competition requirements, and other aspects such as creation of 'legibility' of the lodges array. The team leader was meticulous about 'legibility' issue to express the idea to the jury:

00:16:13 TL: *Now, without a rule, when we get random, it will look as if we just put it randomly. No architect can read that. He or she can't interpret if he/she can't read. Let me tell you so... He should understand it the moment he looks at it.*

The job captain developed multiple alternatives while sketching (figure 1) and calculating the rules and then put the information into the software as 2D drawings (table 1). While sketching the lodge units' organization, the job captain was searching the criteria to have a pattern and image, developed in the meetings (figure 1). Rules were aimed to create legible but at the same time, aimed to express randomness. The job captain about suspicions about randomness:

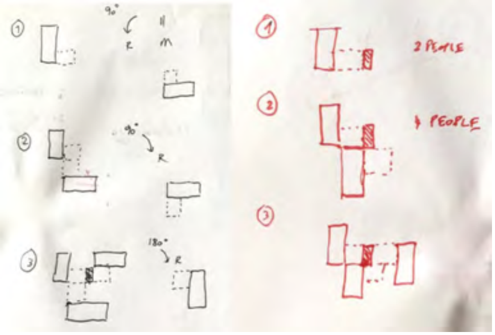


Figure 1
Sketches about the rules, developed by the job captain

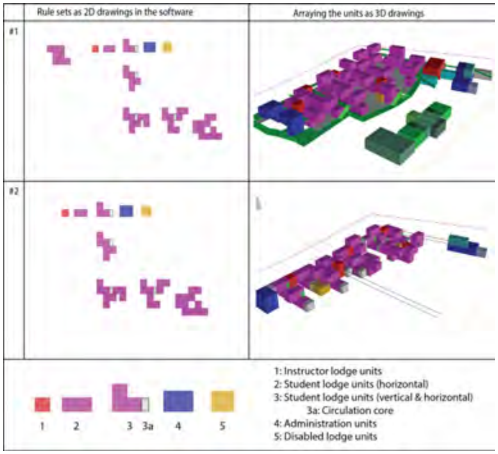


Table 1
(left) 2D drawings of the rule applied units design; (right) 3D drawings of the alternatives: red module

00:00:49 JC: *I really did it with random mirror rotation. Second, it also makes more sense to do so. We're going to multiply this, or I don't know, there will be a unit of 8. I think you put 8, 6, so you made a unit according to the rule. Because it seems to be a little fuller, we made 8 and we did 6, we made 10. Maybe, 3 units, perhaps, disintegrate. Because if we do the same thing all the time, will it get boring? I am thinking about that...*

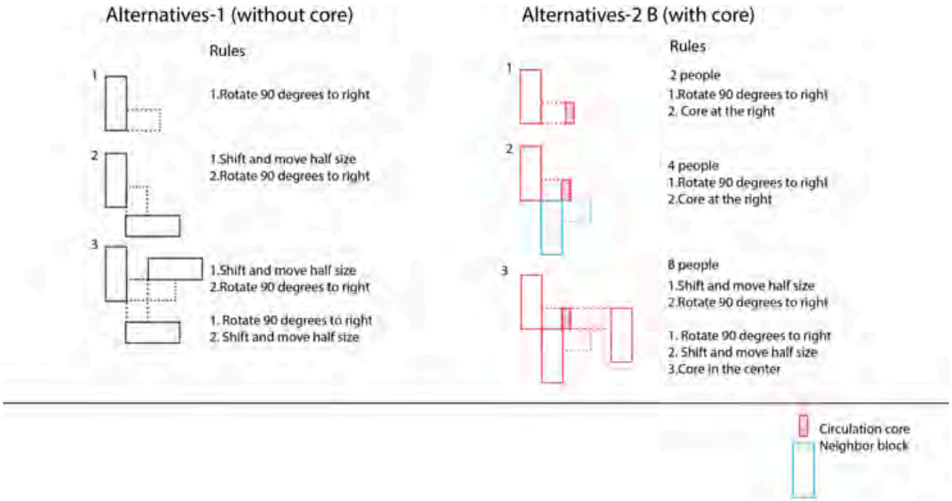
The following figure (figure 2) illustrates and explains the rules that the job captain developed during the design process of the units:

In the following table, some of the alternatives of the units are presented (table1). One of the interesting points that the job captain followed was the steps he took: calculation, drawing, and seeing while sketching. Similar steps were followed in the digital tool, calculation, drawing as 2D, and then to see the created alternative, the job captain applied the rules in the site organization by arraying the units according to rules.

SOLVING DESIGN PROBLEMS BY TOOLS

In this section, we take a look into a part of the competition B where the team leader and the intern architect worked in collaboration in finding façade scheme. In competition B, the team leader dominated the design project more than the project A. Rather than creating multiple alternatives, the team leader described a façade design to the code developer who is also an intern architect (IA1), and then IA1 applied the design idea on Grasshopper by developing rules. In the façade design, wooden elements arrays on the upper floors of the building façade design solutions were applied. The team leader sketched the idea as description of numbers and shapes, then the code developer re-sketched to understand trying to find out exceptional situations such as wooden elements arrays on the corner points of the façade. Afterwards, the code developer developed algorithms and applied on Grasshopper software. In Figure 3, the team leader's sketches are represented. Wooden elements were designed in order to take natural light by filtering into the interior space surrounding of the glass façade. In the sketches (figure 3) the team leader defines the size and proportions of the wooden façade elements. Presumptive perspective and sectional sketches were also developed by the team leader in the meetings. At this point, the team leader gave exact dimensions for the façade elements but façade view and effect were not defined precisely.

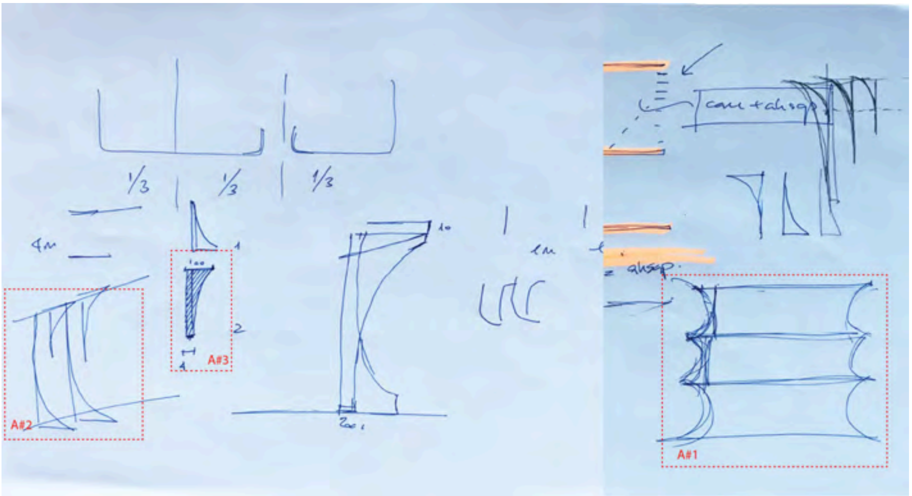
Figure 2
The illustrations and explanations of the rules that developed by the job captain



However, the code developer re-sketched before entering the data (figure 4). Sketches and notes (figure 4) were about the arrangement of the wooden elements on the façade. The sketches represent the elements' dimensions and radius calculations, and the notes are about the wooden elements' placement on the corner of the façade.

In the semi-structured interviews, IA1 explained the rules that applied for the façade works. Once identifying three different types of the wooden elements that would surround the façade, the gaps between the elements were determined. Following that, different ranges and forms were specified as rules, IA1 tested multiple alternatives of the config-

Figure 3
Façade sketches; details and dimensions, developed by the team leader



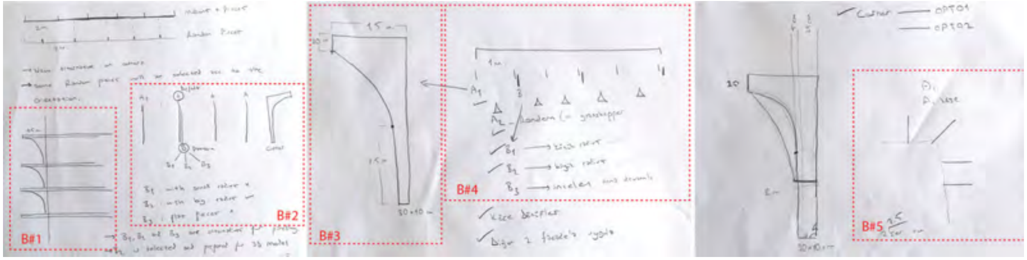


Figure 4
Sketches by the IA1 on the arrangement of wooden elements

uration of the elements on Grasshopper. Within the limits of the rules that are defined by the designer, in the meantime within the flexibility of the rules, the arrangement of the timber elements was calculated through Random-Selection option of Grasshopper. The code developer (IA1) states:

00:03:25 IA1: .... *We also had another situation: randomness. Because of every façade has a different azimuth, for instance we said lets have much more random percentage of elements. We had 50% here, I mean once in two meters, right in the middle of the elements, we had Random in Grasshopper. We applied that in every floor. In this façade, we had 30% because; this façade has sunlight more than the others...*

The rules about the arrangement of the timber elements on the façade, the dimensions of each part, were calculated on paper and sketched, later all the data about the rules were entered into the digital tool (figure 5). On the base of the calculations on paper, IA1 calculated arrangement and percentage of the elements. Random option of Grasshopper calculated possible alternatives. After developing limited alternatives, the team leader decided to develop the façade shown in figures 5 and 6.

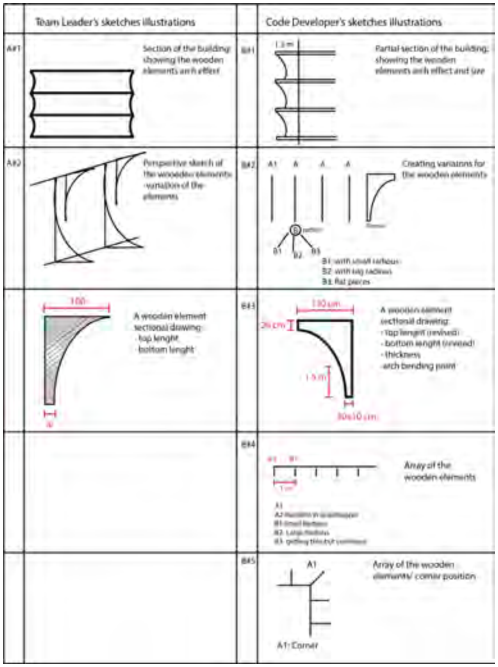


Table 2
Illustrations of Team Leader's and Code Developer's sketches

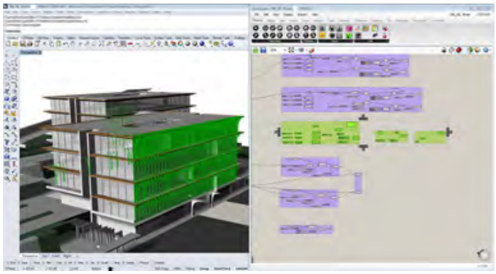


Figure 5
Application of the wooden elements of the façade on Grasshopper by Ihe code developer

Figure 6
The last version of the façade

DISCUSSIONS AND CONCLUSIONS

This research establishes the significance of design exploration by tools in the sense of knowledge propagation between the design object and the designer/s in the design process. The emerging question in this research that computational design tools are explorative as much as conventional sketching or the defined algorithm limits the variety of design solutions. Our claim is that in design process which compromises exploration by sketching and computation may turn into a hybrid practice that complement and feed each other. In both of the competition processes, sketching was one of the main tools that were used in the system as an information propagation tool among the team participants other than computational design tools and other software. Moreover, sketching was also a mediator tool between the code developer and the computational tool; first, the code developer was sketching for each problem then, inputting a set of the rules to the digital tool. Sketching also was an exploration tool in the competition A and manipulations of the shapes were done in order to apply exceptional situations such as disabled users' units design. However, when manipulations applied in a rule-based shape design, in this case we cannot talk about calculation in the design (Stiny, 2006). On the other hand, in the competition B, the code developer was aware of the exceptional situations for the rule, such as wooden elements' array on the corner of the building. However, in the beginning of the algorithm creation, the code developer applied the solution of every situation in the rule.Yu et al. (2015) claim computational design is a dynamic and rule-based process. Computational thinking relies on setting and organizing the rules for development of forms but, designer does not obviously define final form (Poulsgaard and Malafouris, 2013). In competition B, the code developer while defining the parameters including exceptional situations may not be aware of the final form. In competitional design, final design solution does not need to be precise, the random results of computational design can solve a non-fundamental formal design problem. However, in the design process, the interruption of the seeing-drawing-seeing process between designer and design object can lead to an end design arbitrarily.In the design process of the competitions, even though all the team participants were knowledgeable about computational design software, only expert participants took the responsibilities. Shifts in the roles were possible within team participants in the design process but the use of computational tools made it harder for teammates to shift roles. It seems that computational expertise requires a more specialized expertise. While looking for solutions to the architectural design problem, the use of computational design tools by two of the team participants might have influenced the architectural design approach. Moreover, architects who had knowledge of computational design technologies did not use the computational tools in the design process, they applied the computational design approach which they had internalized while using non-digital tools as rule-based sketches to find a solution to the design problem. Moreover, computational tools enable creating multiple alternatives, which one might think would be an opportunity in creating multiple alternatives, but code developers were more concerned with streamlining the process because of time constraints.

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TransDigital

A cooperative educational project between architecture and crafts

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Even though the computer acts as an effective interface for the cooperation of various actors involved in the construction, the success of a project depends crucially on the socio-cultural characteristics and disciplinary boundary conditions of the people involved. In addition to the technological challenges of digitisation, different working methods, requirements and objectives often represent an obstacle to the successful cooperation and execution of architectural projects. This is where we as a university are challenged to point out new ways that are geared to the future requirements of our professions and, as it were, integrate individual professional profiles. Against this background, the cooperative education project brought together architecture students and trainees in the carpentry trade in order to help them gain an understanding for their respective differing approaches and for their own expertise at an early stage in training, and thus experience the added value of a cooperative working method. The teaching of digital design and planning methods as well as the use of computer-aided production technologies were the vehicles for networked cooperation and integrative learning.

Keywords: *cooperative learning, interdisciplinary collaboration, architecture curriculum, digital design and fabrication*

1. INTRODUCTION

The progressive digitisation of the development and production processes in architecture has a major influence on job profiles in the planning and building industry. The computer has become indispensable in the design and planning process of architects and specialist planners. The production and assembly of buildings, rooms and objects is also becoming increasingly based on digital technologies. Even though the computer acts as an effective interface for the cooperation of various actors involved in the construction, the success of a project depends crucially on the socio-cultural characteristics and disciplinary boundary conditions of the people involved. In addition to the technological challenges of digitisation, different working methods, requirements and objectives often represent an obstacle to the successful cooperation and execution of architectural projects. This is where we as a university are challenged to point out new ways that are geared to the future requirements of our professions and, as it were, integrate individual professional profiles. The transfer of information and knowledge between different job profiles as well as interdisciplinary and intercultural cooperation should be strengthened. To this end, new methods of knowledge transfer are needed.

Against this background, the cooperative education project TransDigital brought together architecture students and trainees in the carpentry trade in order to help them gain an understanding for their respective differing approaches and for their own expertise at an early stage in training, and thus experience the added value of a cooperative working method. The teaching of digital design and planning methods as well as the use of computer-aided production technologies were the vehicles for networked cooperation and integrative learning.

But how do architects and carpenters work in the age of digitalisation and what do you need for successful cooperation between the two disciplines? And above all: How can we design a learning environment that enhances the idea of this collaborative approach. Based on these questions, 12 students and 12 trainees developed and implemented the spatial concept RandomizeBox/Co-Working Space working in interdisciplinary teams.

2. EDUCATIONAL CONCEPT

2.1 Didactic approach

Walter Gropius, looking back at the Bauhaus, described an approach towards the new technologies of the time that provided an important impetus for the didactic concept of the cooperative project: "Our objective was to eliminate the draw-backs of the machine without sacrificing any one of its real advantages. Experiment once more become the center of architecture, and that demands a broad, coordinating mind, not the narrow specialist" .

Trying out, testing, crossing borders, exploring, discovering and "making" is originally associated with the development of architecture. The experiment not only dissolves the boundaries between research, teaching and practice, but also creates a change of perspective from teaching to learning. Hence, the following didactic models support the didactic approach:

- The theory of Design thinking forms the conceptual framework for the desired creative development process and interdisciplinary exchange. It is based on the assumption that problems can be solved better if people from different disciplines work together in an environment that promotes creativity, jointly develop an issue, take people's needs and motivations into account and then develop concepts that are tested several times.

- Research-Based Design describes a research-led development process. The design method is oriented towards the construction of prototypes and includes the exploration of various design concepts as well as the process-accompanying evaluation of the results and successive optimization of the proposed solutions.

- Design-Build projects combine practice and teaching. The realisation of a building, from the conceptual idea, through design and planning to execution, is carried out jointly with students. If one understands the structural implementation as a goal of the creative activity, the examination with the construction and building offers an enormous learning potential.

2.2 Preparation phase

TransDigital was developed as an experimental cooperation between the partners, without a concrete reference project which could be built on. Although there was previous knowledge and project experience on both sides that flowed into the educational project, the consistently discipline-spanning orienta-

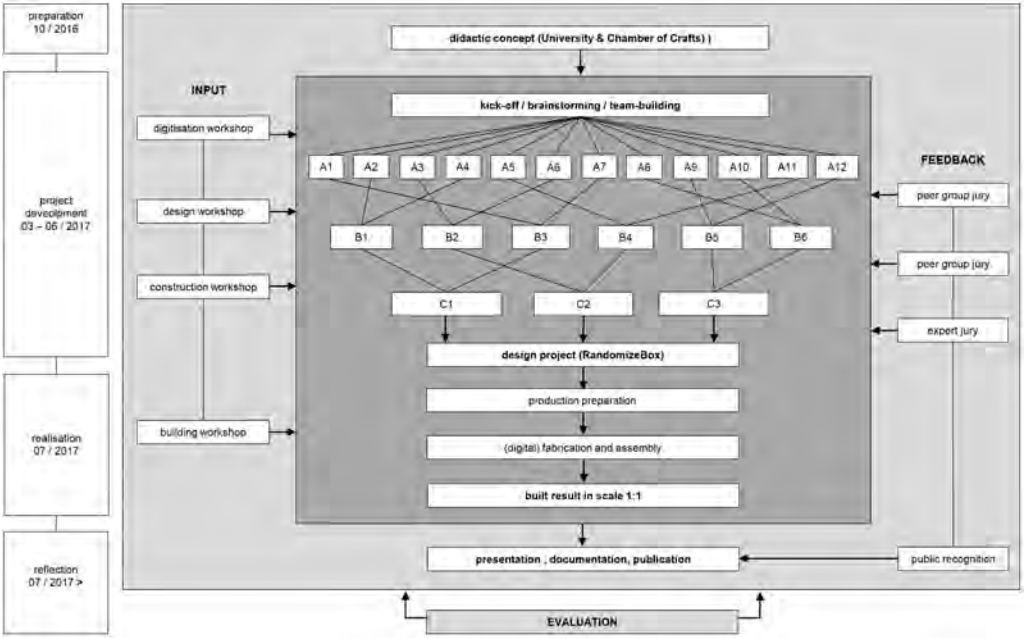

Figure 1
Didactic concept and structure of the collaborative project.

tion represents a new approach, both for trade training and for architectural studies at the university. The teaching and learning format was therefore developed specifically for the different perspectives and requirements of both parties and could serve as a prototype for a new type of training in architecture and trade.

In developing the concept for the cooperative training project, it was essential to create a safe and activating learning arrangement for students and trainees. The change of perspective from teaching to learning was the starting point for the design of a motivating and successful teaching and learning environment for both cooperation partners. The teaching model was deliberately designed as an open-ended bottom-up structure so that participants could actively participate in the development process. In the 2017 summer term, the cooperative and experimental approach was implemented at the Faculty of Architecture in cooperation with the Chamber of Crafts in Cologne as part of the elective Bachelor module "Building with the Computer". The TransDigital diagram serves to illustrate the didactic model and the project progression, which is described in more detail below.

2.3 Kick-off

The experimental module started with a kick-off workshop which, after an introduction to the subject, directed the students and trainees into an active and creative role, in which they formulated individual requirements from their areas of knowledge and experience in writing and presented them to the group - according to the "Think-Pair-Share" principle of cooperative learning . As a result, the first focal points emerged, and a common understanding of the project was significantly enhanced right from the start. The event also formed the basis for the formation of 12 interdisciplinary teams, which subsequently developed initial ideas for a common workspace for architects and carpenters.

2.4 Project Development

A competition structure consisting of three consecutive selection stages (quarter-final, semi-final and final) was defined as a conceptual framework for action. The teams thus developed a large number of innovative approaches at short intervals. Following the credo of Nobel Prize winner Linus C. Pauling: "The best way to have a good idea, is to have a lot of ideas" .

The supplementary teaching and learning modules used in the course of the project were integrated into this structure as input and feedback loops. The input topics were incorporated by the lecturers of the university and the trainers of the Chamber of Trades and Crafts (HWK) or also jointly in the form of workshops (digitisation, design, construction, building). Meanwhile the feedback loops consisted of moderated Peer Group juries (students and trainees evaluating the work), in which the presented project ideas were discussed, with proposals made for the next stage of the competition. Individual solutions were selected, and new teams were brought together for the next round. In the course of the competition, the number of teams (12 > 6 > 3) was halved and the number of members per team doubled with each competition level. Consequently, project ideas were worked out in greater detail, and discussions and exchanges between the participants were intensified.

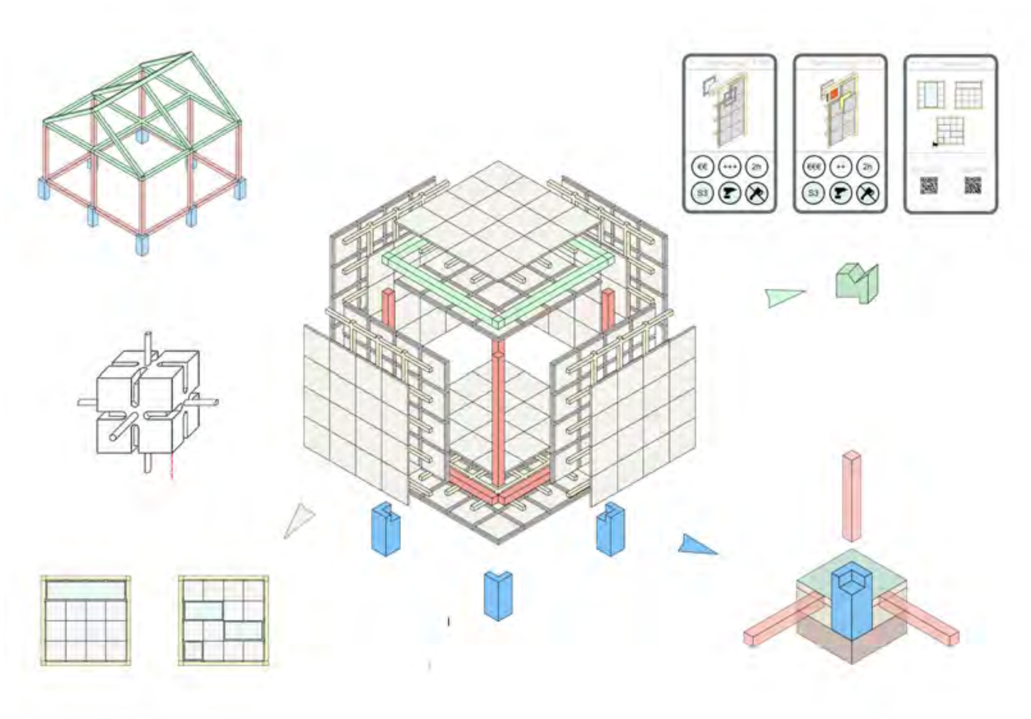

Figure 2
Design concept of the modular prototype "RandomizeBox Co-WorkingSpace".

The final judging in the final round was carried out by independent experts from both disciplines (university and trade) who were previously unfamiliar with the project. The classification and appreciation of the work "from the outside" led students and trainees to identify even more strongly with the project. At this stage, too, partial aspects of the work were selected and finally merged into the RandomizeBox/Co-Working Space integrative concept.

2.5 Implementation phase

In architecture, structural implementation is the goal of the design phase. Or as the German graphic designer Otl Aicher put it: "thinking is the flipside of doing" . In this respect, the examination of the boundary condition of the implementation generates enormous learning potential, which consequently also plays a central role in the TransDigital project. For students in particular, this phase was characterised by a steep learning curve.

In preparation for the structural implementation, the teams were divided into thematic groups, so that development of a central digital model, structure design, development of usage scenarios, identification and ordering of materials, workflow planning as well as assembly and structure strategy, could all be developed in parallel. This method of working required a clear organisational structure, which was set up in the form of work plans with a clear division of tasks. The central data model of the design served as an important decision-making and communication instrument throughout the course of the project. Based on the open source concept, this digital 3D model was accessible to everyone involved in the development process. This OER (Open Educational Resource) was set up on a server of the Faculty of Architecture with access for all participants . The students and apprentices were thus able to be interactively integrated into teaching/learning processes in the sense of research learning using digital technology . With regard to architecture as a design discipline, this approach is based on the principles of Design-based research , which use a combination of practice and theory to generate knowledge at the centre of the educational concept.

The wooden components of the RandomizeBox and the furniture of the Co-Working Space were manufactured and then assembled together in a two-week construction workshop at the Butzweiler Hof training centre. Since many decisions had to be taken during construction-related planning, close coordination of the work processes was necessary. The individual production steps were therefore precisely prepared by the trainers to ensure a smooth process. The self-motivation of the participants and the fact that the teams were already working very well together at this time contributed significantly to the experimental construction being completed in the given time and allowed them to take pleasure in doing so. The result of the cooperation - a flexible, modular timber construction system based on the open source concept - represents an innovative approach to future construction. The design principle is openly available in version 1.0 and can therefore be further developed and adapted to the respective requirements.

3. CONCLUSION

One of the main challenges of the project was the organisational coordination between the cooperation partners involved. The different time and administrative requirements (e.g. term structure/examination periods vs. vocational school agenda/requirements of the training companies). This required a high degree of flexibility and commitment from all those involved. Furthermore, it must be noted that the set scope of the project (bottom-up process, multiple judging steps and 1:1 implementation) partly overstretched the one-term formats. In future projects, more time should be allowed for the implementation phase and its preparation. The bottom-up approach also led to a certain overload in some participants, which consisted in the fact that the prerequisites for one's own actions and thinking partly had to be created first. A clear specification of the steps to be carried out and the concrete formulation of

Figure 3
Collaborative working process from digital design to manufacturing.

Figure 4
Assembly of the modular wood structure

Figure 5
Digital design model and final structure of the RandomizeBox / Co-Working Space.

the expected result was deliberately not introduced from outside in the inductive approach but developed step by step within the team in the processes.

Nevertheless, learning success was consistently assessed positively by all participants. This notably applies to the cooperation itself. The intensive exchange of opinions, knowledge and experience as well as the new understanding of the respective own and other disciplines were among the essential findings of the education project. In addition, digitisation was often recognised as an opportunity for improved cooperation and a networked working methodology. Over the course of time TransDigital has developed a valuable momentum of its own, which came from the participants, but also supported and further motivated them. This was made clear above all by the high level of personal responsibility and initiative of students and trainees, after completion of the actual module. One year later, the project remains active.

4. OUTLOOK

The successful cooperation will be further developed in a follow-up project during the 2019 summer and winter term. The Building Information Modeling (BIM) planning method forms the basis for an extended cooperative approach that aims at a realization of a new digital laboratory on the university campus, involving additional institutes(civil engineering, project management, energy-optimized construction) and external project members (City of Cologne, industry partners). The aim is the interdisciplinary development and realisation of a timber construction system in self-construction as part of a teaching and research project at the Cologne University of Applied Sciences. The findings from the project are to be transferred into a curriculum and consolidated at the Faculty of Architecture.

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FavLab Maré Edition

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This paper introduces and discusses the first outcome of a recently created digital fabrication laboratory at Favela da Maré, a slum in the North zone of Rio de Janeiro, Brazil. The lab called FavLab is a partnership between the João e Maria Aleixo Institute, located inside Favela da Maré, and the Department of Architecture and Urbanism of PUC-Rio University. More specifically, it aims to present the lab's first activity: a workshop devoted to create and fabricate meaningful objects to the context of favela exploiting digital design and fabrication methods. Architecture undergraduates and local young residents not enrolled in the educational system participated in the studio. This paper aims to discuss in details the experience of teaching for this particular group of students, as well as the impacts of the collaborative design between university and favela students to create interactive objects in a Brazilian community. The paper aims to reinforce and remark an innovative and inclusive approach to digital design and fabrication. This paper also attempts to discuss further developments and next steps towards more profound and broader collaboration between academia and favelas' representatives.

Keywords: *Fab Labs, Favela, Interactive installation, Parametric design, Digital fabrication*

INTRODUCTION

"Architects tend to be slow on embracing new Technologies," says Mario Carpo (2017). The First Industrial Revolution (1750-1830) focused on coal, steam engines, railroads, and textiles (Gordon, 2017) had no significant impact on architecture (Carpo, 2017). It also took some time for architects to embrace new industrialized materials and technological processes (Carpo, 2017) made possible by the Second Industrial Revolution (1870-1900) carried off upon electricity, internal combustion engines, modern communications, entertainment, mass production, petroleum/hydrocarbons and chemicals (Gordon, 2017). Contrary to this historical tendency, architects were the first in the creative industry to understand the changing power of emerging digital technology of the Third Industrial Revolution (Carpo, 2017), initiated in the 1960s and revolved around computing and telecommunications (Gordon, 2017). Architects were the first to realize that digital design and technology meant to produce variations, not identical copies; customized, not standardized products (Carpo, 2017). Since then, it has been changing the way we think and produce architecture (Menges, 2015).

Fast forwards to the 2010s, the most advanced “digitally intelligent architects” (Carpo, 2017), claimed that the world has entered into a new industrial status: The Fourth Industrial Revolution. This contemporary industrial condition, which was also the central theme of The World Economic Forum 2016, is defined by the German economist and inventor of the “exclusive Davos Club”, Professor Klaus Schwab (2017), as “the inexorable shift from simple digitization (the Third Industrial Revolution) to innovation based on combinations of technologies (the Fourth Industrial Revolution) ”. In Schwab’s vision, the key technologies driving this revolution are actually “a fusion of technologies that is blurring the lines between the physical, digital, and biological spheres.” The increasing complexity of the core machines of each revolution was nicely illustrated in the famous Achim Menges’s paper “The New Cyberphysical Making in Architecture” (Menges, 2015), where the author claims an “upcoming paradigm shift in production (...) referred to as Industry 4.0”, characterized by a much higher level of integration and cross-linking between the physical and digital domains. New manufacturing machines and robots have started to gain communication, monitoring, and sensing capacities, and with this, the ability to react and, ultimately, to act, opening the door for the next leap forward in production technology.

According to the economist Jeremy Rifkin (2014), an industrial revolution is foremost an infrastructural revolution that depends on a tripod of communication, energy, and transport/logistics. Schwab’s main argument in favor of a new industrial revolution instead of an extension of the previous one relays on qualitative aspects of “velocity, scope, and system impacts” (Schwab, 2017). Rifkin (2014), differently argues that it is the decreasing fixed costs of digital technology, its “near zero marginal cost,” and the intrinsic interconnected nature of the technology itself that has enabled a qualitative jump in scope, velocity, and systems impact for the past twenty-five years. Rifkin’s vision offers a more inclusive prospect and a much broader horizon of possibilities, especially for architects working in developing countries.

In this paper, we aim to discuss a shifted, broader view on what does constitute an industrial revolution, based on Rifkin’s concepts, more focused on what technology does rather than in its effects. In other words, instead of focusing on the technology itself, we aim to focus on its social implications. Digitally intelligent architects have been designing and accumulating expertise in adapting existing tools and developing their own for the past thirty years. Albeit the maker revolution coupled with the near-zero marginal production cost, both established upon digital processes, represent new opportunities, it may cut both ways: it may greatly expand the distance between the most advanced research centers and developing countries, or it may genuinely approximate both worlds, since technical knowledge and tools are more accessible than ever. Thus, it may also help growing architects’ ability to act within the community and to generate significant social impact. Ultimately, digital manufacturing in architecture can be a very efficient way to democratize architectural design where it is needed the most truly. Like Cedric Price, we do believe that technology is the answer, but we have different questions, and in this work, we intend to address some of them.

OPAQUE TERRITORIES

The core definition and production of technology, as well as the technological agenda, is customarily ranked by the North developed countries. Developing countries are supposed to follow their lead and import their technology (Santos, 2002). Indeed, current techniques are universal. However, they are introduced in different modes and intensities, according to their features and the location in which they are installed. The absence of representatives from developing countries in the broader discussion panorama about any global technological commitments and concerns is remarkable. In a counterpoint, the concept of “peripheral technology”, introduced by the Brazilian geographer Milton Santos (2002), a Vautrin Lud Prize winner, help us to set a distinct and inclusionary theoretical background, as well as to discuss the meaning and to add value to a bottom-up participative approach on parametric design and digital fabrication considering local and social requirements.

Santos (2002) defines as "luminous territories," those rationalized areas that accumulate technical and informational densities, and therefore, are more attractive to finance capital, technology, and organization. "Opaque territories," on the contrary, lack access to them. Santos (2002) explains that there is a limited production of rationality, that is, luminous spaces, associated with a widespread production of scarcity - opaque territories - that leads the actors outside the circle of hegemonic rationality to a self-consciousness of their exclusion which in turn, leads to the search for alternative forms of rationality, indispensable for their survival. Inorganic spaces such as opaque territories are unclosed systems that cannot be wholly subordinated to the dominant rationalities since they do not have the means to access contemporary production techniques. This experience of scarcity is the basis of a creative adaptation to the current reality. In this sense, opaque territories are the spaces of approximation, creativity, and bottom-up specialization. Opposite to luminous zones, reigned by top-down specialization of exactness, ruthless standards, and search for precision in production processes. It does not mean that developing countries are purely opaque, but rather that the development condition in architecture is uneven compared to developed countries considerations on technological innovation. Therefore, both the very notion of technology is not necessarily the same, and neither the intersections between technology and architectural design should have the same aspirations. Different problems and distinct realities should lead to diverse responses and specific appropriations of technology.

The recognition of the expertise and the technology developed locally, solidly anchored in the contextual reality of the architects working in developed countries, are fundamental factors to pave the next steps. Indeed, the technology historicist Melvin Kranzberg (1986) remarkably stated that technology is never neutral. On the contrary, in his words: *"technology's interaction with social ecology is such that technical developments frequently have environmental, social and human consequences that go far beyond the immediate purpose of the technical devices and practices themselves, and the same technology can quite have different results when introduces into different contexts or under different circumstances."*

Aligned with the logic of non-neutrality, Kranzberg goes further and explains that "nontechnical factors take precedence in technology-policy decisions." No decision is purely technical, especially when human elements are involved. The impacts of technological decisions in social terms is in particularly imperative in complex sociocultural environments such as favelas. Since technology is understood as a non-neuter artifact, technology-based entrepreneurship may acquire a social function and play a crucial role in promoting a profound transformation in knowledge dissemination and technical production. Tuned in to Melvin Krazberg's third law (1986), suitable technological solutions for one context may be inadequate for another. Thus, research on which specific questions that digital manufacturing can help us addressing to is vital.

In this sense, importing technological models from developed countries to the reality of developing countries always requires tremendous adaptation efforts, due to their asymmetric levels of socioeconomic, scientific and technical development. Emerging countries, such as Brazil, are continually struggling against their significant limitations in their development standards (Feldman, 2009). Besides, decades of low investments in high-level technology research have considerable damage to industrial processes updating as a whole, architecture included (Feldman, 2009). This scenario dramatically reduces developing countries capacity in fostering high technological content production, in generating quality employment, and in promoting social well-being (Feldman, 2009).

The technological entrepreneurship emerges as a strategy for a gradual improvement of the internal capacity to manufacture products with technological content, and as a means to propagate knowledge generation through the production chain (Vieirra et al., 2017). Small local initiatives are much more accessible, affordable, and may address problems faced on the local level that high-end technological solutions may not (Gershenfeld et al., 2017). Plus, the high productivity of digital processes associated with extraordinary adaptability, upgrade capacities and the near-zero marginal production cost (Rifkin, 2014) together set a favorable stage to flourish a new status for architects working in developing countries, at least in theory.

However, the capacity to transform new knowledge into economic opportunities involves a set of abilities, skills, perceptions, and circumstances that are far from being uniformly and widely distributed in society (Audretsch, 2006). In this scenario, the Fab Lab network has demonstrated to be an important strategy to leverage economic objectives and to produce wealth in developing countries (Vieira et al., 2017). With the maxim "Learn, Make, Share," these spaces aim to empower its members' ability to build local, sustainable community-based solutions by using open source tools and digital fabrication technology. Besides the promotion of innovation, Fab Labs also allow the creation of low-cost products very quickly and test their acceptance by the community, leveraging improvements that will make these solutions evolve collaboratively (Gershenfeld, 2017). So, deep social bonds are a crucial aspect. Since Fab Lab is an imported model, this active social link prevents alien solutions. Instead of merely introducing technology - that is, consuming technology - these labs support the creation of technology locally (Eychenne et al., 2013).

In socially complex environments such as favelas, collaborative spaces like Fab Labs can play an influential role in providing knowledge tuned in to worldwide technological updates and access to productive means. It can breed new solutions to start reestablishing the balance between luminous and opaque territories in developing countries' communities. Fab Labs are the educational component of digital manufacturing awareness that favors the democratization of technological concepts and techniques. Fab Labs in favelas can also function as incubators of local innovation enterprises, and as decisive alternatives for those who abandoned formal education.

The well-succeeded experience of Free Fab Labs in São Paulo, Brazil, provides valuable contributions. The results of recent research on the labs' contributions to the surrounding communities point them towards a viable alternative to unemployment (Vieira et al., 2017). Foremost, the labs were indicated as a potential opportunity for a whole new generation of technology entrepreneurs fully ready for adopting the principles of sharing economy (Vieira et al., 2017). While financial scalability and sustainability remain a significant obstacle for entrepreneurship in developing countries, Fab Labs can open big windows towards digital inclusion, once they are supposed to build bridges between professionals and non-experts, high-tech fabrication and local analog technology, academics and artisans. Fab Labs in favelas can be a turning point for community members; for architects, they can be essential mechanisms for professionals interested in proposing solutions to these territories. The crucial difference is that the labs also allow the fabrication of these solutions, fostering the architect's immediate action.

FAVLAB

The adoption of digital processes in architectural design and fabrication in developing countries has been slow (Sperling, 2015). In poor areas, access to such technologies is even slower and very limited. Slums are the most opaque of the territories, where design and technology are considered unnecessary luxury compared to unfulfilled basic needs imposed on these populations. According to the United Nations (2016), favelas represent around one-third of the developing countries' territory, and they accommodate around one billion dwellers around the globe. Favelas are often recognized for what they lack: infrastructure, urbanization, architectural quality. However, it is the same restricted access to technical means that nourishes what Brazilians call 'technology of scarcity,' where creativity and technological innovation, such celebrated concepts in contemporary digital architecture, are the means of survival fueled by the lack of resources. In other words, this "fundamental lack produces a creative discomfort" (Santos, 2002). Favela's dwellers are hackers and makers by necessity. Krazberg (1986) states that "invention is the mother of necessity." We dare to invert the sentence and say that when it comes to favelas, necessity is the mother of invention.

Architects usually understand favelas as a design problem or as an object of morphological analysis. Annually, dozens of researches carried out in slums exhibit amazing designs solutions. Most of them have low impacts on local architectural production or labor, with no significant technological knowledge transference to the dwellers or any absorption of local technologies or aesthetics. We aim to offer a different approach, in which digital design and manufacturing can play a crucial role in transforming this kind of territory. The core concept is adaptation, whether in site-specific and parametric variation design approaches or in adapting possibilities of digital design and fabrication to local conditions. The fusion of suitable technologies with access to productive digital processes opens up a myriad of possibilities regarding participatory design. It also implies new meanings to digital design in social terms.

The idea of favelas' digital fabrication laboratories - FavLab - has emerged as a way to connect the academic digital processes with the technological inventiveness of favelas. The therm FavLab is directly related to the global network of digital fabrication laboratory initiated in the MIT Media Lab, headed by Neil Gershenfeld. The FavLab was initially idealized in 2012 and presented to Fab Foundation Director, Sherry Lassiter in 2015. It finally got a kick off in 2019 at Favela da Maré, Rio de Janeiro, as the result of the collaboration between a local institution called 'Instituto Maria e João Aleixo' (IMJA) and the Department of Architecture and Urbanism at PUC-Rio.

FavLab Workshop Maré Edition

The first initiative of this recently created laboratory was a workshop between architecture undergraduates and local young residents not enrolled in the educational system, working together to design and construct meaningful objects for the favela's public space. The final location of construction could not be previously settled because it depended on negotiations between local leaders and other actors (drug lords, militia). So, parametric design played an essential role in fitting the proposals to any context. The group of 30 students - 12 from IMJS e 18 from PUC - two teachers from the university and one teacher from the community was very interdisciplinary with quite varied backgrounds.

The two-week course ran from January 28th to February 8th. It was partially held at the university and IMJA located inside the slum. Classes and digital fabrication were carried out at the university's laboratories. In the first week, students had lessons, visited the site, and developed the design ideas. A professor specialized in urban anthropology was invited for a lecture to help to set the theoretical background. In the second week, students were devoted to designing adjustments for fabrication and assembly. The workshop was divided into three phases as described in the sections bellow.

1. Modeling training and digital fabrication tooling. All students indistinctively attended to Rhinoceros, Grasshopper, Arduino and digital fabrication classes. Most students from both institutions were not experienced in any of these topics. Parametric design classes were prepared considering popular cheap materials such as bricks and pipes that could also resist exposure to weather and vandalism. Six parametric design exercises from introduction to intermediate included attractor rotation, list manipulation, cellular automata principles, pseudo-physics simulations with Kangaroo, weather-responsive behavior with Ladybug, and introduction to interaction design with Firefly and Arduino.

Digital fabrication classes included milling routines in router CNC, 3D printing, and laser cutting. Although many Maré students did not have any formal academic training, in most cases, their electronics and programming skills were superior compared to scholar participants. Therefore, the shared expertise in both directions was crucial for the whole experience achievement. One revealing observation was that learning 3D modeling or even parametric design principles were not the main barriers for favela's students, but language was since Rhino and Grasshopper installations were in English.

2. Design conception. Students were divided into four workgroups to create four different design proposals. The groups had equal proportions of students from PUC and Maré. Interactive behavior, parametric adaptation, materials, and digital fabrication process had to be considered. The proposals, illustrated in the pictures below, were presented in the favela and were submitted to the scrutiny of the local leaders. The ideas were evaluated regarding their relevance to the population, feasibility, and budget, and some adaptations were required.

Maré students were important beacons for the projects, and some compelling observations came to attention during this process. It became evident that parametric iconography, or parametricism as an aesthetic style, as Schumacher (2011) claims, was not particularly appealing for those students. Both favela's participants and architecture students were slightly more interested in parametric design as an essential platform to develop ruled-based designs, which allows quick site-specific adaptations than in its potentials of fostering formal expression. Even though aesthetics played a significant whole, the pursuit of meaningful and rational designs outshined any search for amusing meaningless forms.

Customization and hands-on approach are not fully disseminated in Brazilian architecture schools. However, it became clear that these concepts per se were not unfamiliar at all to Maré students and not especially attractive because they regard it as common ground. On the other hand, they considered prospects of digital fabrication stimulating. The main spotlight, though, was interactive design. Although it was not a workshop's premise, most understood that their projects would be more compelling to the public if they could behave in a specific manner. As a result, three proposals were performative-oriented designs, and one project focused on generative adaptative design based on cellular automata.

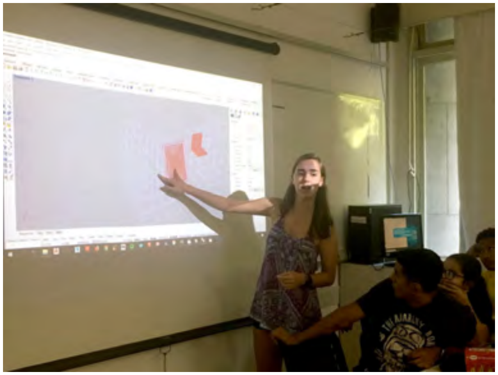

Figure 1
Student explaining the cellular automata logic applied to create an extension to the children's library.

Figure 2
The group discussing ideas.

Figure 3
Students setting interaction programming.

Figure 4
The group testing the effect of the light inside the pipes.

Figure 5
Students inside the children's library, setting the pipes for construction.

Figure 6
Led Stripes, sensors and electrical connections being set.

Local students chose a square next to the public library to hold the interventions. Due to time restrictions and budget limited to the equivalent of 200 Euros, the group had to decide collectively for only one proposal. The chosen one was an interactive light sculpture for children activated by the voice, to be installed next to the children's library. It consisted of a series of interlaced pipes where children could tell secrets to one another. The children's voice power activated led stripes placed inside the pipes. The louder the children, the brighter the lights. The concept behind this ludic toy was to give voice to the residents of the community, especially the children. The statement behind the funny game was making it evident that all voices are powerful, that all voices can and should be heard. Students had to combine a mix of digital and analog manufacturing processes to gather the installation. They also set up sensors, programming behavior and electronic circuits.

3. Construction. The groups were merged to assemble the interactive installation on site. The pipes were perforated to let the lights come out. A perforation routine and a CNC milling machine were used for the task. The pattern of holes was designed parametrically in Grasshopper. All the pipes received an internal acetate plastic lining to prevent sound escaping. It also acted as a light diffuser, so the led balls were not too visible. The group got the acetate by removing the black material (photo-emulsion) from x-rays leftovers with bleach.

Due to climate conditions, the assembly ran on February 20th - 21st, almost two weeks after the workshop's conclusion, with the full participation of resident children. A group of graffiti artists from Maré painted the installation wall with relevant local characters. The children's initiative in taking part in the assembly was fascinating to watch. They decided the colors of the pipes, how they should be painted and, finally, they decided to decorate the tubes themselves. The sound capture sensors and all the electrical connections were positioned inside the 3D printed speakers.

Figure 7
The connection between sensors and Arduino being set.

Figure 8
Children volunteering to test the interaction.

Figure 9
Children testing their new toy.

The toy was a great success. Children were amused, playing around to discover which pipes were connected and testing the volume of their voices. It is also worth mentioning that the hostile environment did not prevent the team from proposing and setting up this toy for children at a public space inside a favela. However, it would not be possible without the decisive mediation between the institutional partners from Maré and local forces, such as drug lords, residents' association, and local volunteers.

After the workshop, students answered a survey about the course. The inquiry addressed three questions on students' capacity in following classes, if they considered results relevant for the favela and if they feel that the proposition of holding a digital fabrication in a slum - the FavLab - should progress. The form also included a section for free comments. Despite the differences in educational level between participants, the students' majority declared no struggles in following the lessons. PUC's students were instructed to listen carefully to dwellers and Maré's workshop participants to beacon the projects. The strategy succeeded, since all students related to the proposals and felt a connection between design, site, and users. Finally, all students recognized the FavLab as an essential acquisition for the favela and self-declared the intention to continue in the project. In the free comments section, four testimony from a favela's participants were particularly gripping. In different manners, those students declared that the prospect of attending to a course or using a digital fabrication laboratory at the university was beyond their possibilities, especially a nonpublic one as PUC-Rio. Statements like this reaffirm the importance of the FavLab and rekindle hope in a better future.

FINAL REMARKS AND FURTHER DEVELOPMENTS

In this paper, we aimed to present and detail the background of an innovative workshop, whose basic premise was to gather students of approximately the same age, but with very distinct social origins and educational levels. The strategy was successful. Despite the limitations, all the students were able to follow classes, and the local population recognized the results relevant. Therefore, the objects proposed and constructed by this particular group of students constitute a remarkable statement. The experiment also opens up promising prospects for the future developments of the FavLab. It also reinforces the thesis that Fab Labs can extrapolate its original function and acquire a more in-depth social service. The core assumption of social engagement promoted by the Fab Lab network may be a valuable alternative for entrepreneurship in favelas and an efficiency gain instrument for architects interested in working in these territories.

We also aimed to demonstrate that to grasp the reality of digital design and fabrication in developing countries, the adoption of a localist approach it is not enough since these technologies are universal. On the other hand, Santos (2002) advises us to avoid the "risk of losing ourselves in blind simplification" by taking into account the particularities and specificities of those territories instead of merely considering digital design and fabrication as a general phenomenon dominated by global social forces. The installation described in this paper highlights that favelas' dwellers are unconventional recipients of digital design and fabrication efforts. Including this population in the discussion open up a new, unprecedented debate with the consolidated digital communities: listening and learning from favelas, how they reevaluate the technosphere and find new uses and purposes for objects and techniques. This search for alternative paths initiated with the FavLab is an enlightened vision of the desired future that differs from present subordination of instrumental logic. It is one step closer to the democratization of a reinforced individuality established upon the digital, which goes beyond the barrier of repetitive praxis and sets in a liberating praxis, "the inventive praxis" of which Lefebvre (1958 *in* Santos, 2002) speaks.

By the time of this paper is released, the FavLab Maré implementation inside the favela will be still in process. Until then, former workshop students and volunteers agreed to continue developing their proposals for construction. The pipes toy evolved to a more significant project called *Vozes da Maré* (Maré's Voices), expansible to other slums with the title *Vozes da Comunidade* (Community's Voices). The idea is to expand the toy's function to a more politicized instrument of social action. The central goal is to build a platform of free speech and expression for the people coming from these communities, often ignored. The structure consists of a tubular system similar to the toy, equipped with sensors that capture and record sounds. Lights will be activated by a presence sensor to indicate the recording start and end. A voice recognition system transcribes speeches into text. The people's petitions, aspirations, and wishes in the textual form will be projected live in windowless façades throughout the city. Thus, they become visible to the rest of the town, extrapolating the isolation and segregation in which many favelas' dwellers live.

Of course, this renewed version of once a playful toy proposed by students depends on a series of design improvements, robust programming, research on Big Data, materials investigation, and capital investment. Tuned in to the spirit of local entrepreneurship, digital inclusion, and technology transfer as the FavLab's essential goals, the development demands the full participation of Maré's digital programmers. This project's updates and other FavLab's initiatives, including city sensing, smart 'favelas' and virtual reality for social engagement are available on website www.observatoriodefavelas.org.br.

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abela Paredes, Jorge Juan Rodrigues, Luan Lira, Luisa Eleda, Luísa Valverde, Maria Clara Herdy, Mateus Carvalho, Pablo dos Santos, Raphael Younes, Renata Oliveira, Rhayssa Dandara, Suzana Bentes and Willian Nascimento. Staff: Antônio Messias and Diogo Luz.

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Physical Computing, Prototyping, and Participatory Pedagogies

Make-a-thon as interdisciplinary catalyst for bottom-up social change

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This paper describes a recent make-a-thon event to engage architecture students with physical computing systems while working with engineering and entrepreneurship students. Focusing on the scale of the object or device, the pedagogical goals were to create a productive, transdisciplinary exchange--a pluralistic blend of design charrette, engineering hackathon, and entrepreneurial pitch competition. The Arduino platform and active learning methods were deployed in order to engage with a novice, diverse group of students, leading to outcomes that were responsive to the ever-shifting technological landscape and could be spun into future commercial ventures.

Keywords: *Physical Computing, Prototyping, Pedagogy*

INTRODUCTION

The traditional role of the architect as form-maker and representationalist is being increasingly challenged as systems grow in complexity amidst disrupting technologies foregrounded by environmental degradation and precipitating diverse social issues-the incoming 4th industrial revolution, notwithstanding. However, as architects' individual roles shift in relation to the built environment, pluralist methods of pedagogy can catalyze new models of architectural agency by exploring physical computing and prototyping as bottom-up social change in a participatory design context-integrating an interdisciplinary approach that hybridizes production modalities from contemporary 'hackers' and 'hustlers' (engineers and entrepreneurs, respectively). Ezio Manzini similarly emphasizes this perspective shift of looking at a city as organizations of people rather than buildings in order to design for social change (2015). As methods of the architect are analyzed, so too will the engineer's and entrepreneur's to discern where a productive exchange can take place for building bottom-up social change.

Therefore, with make-a-thon as method-which blends a design charrette, an engineering hackathon, and an entrepreneurial pitch competition-this paper examines participatory pedagogies with tech-augmented material engagement and radical pluralism. Using the make-a-thon as a case study for prototyping a participatory design pedagogy, a new hybridized language of design is seeded in a collegiate environment: students work in interdisciplinary teams, learn new skills (such as hacking/making with Arduino), and scope solutions for problems they identify-ultimately testing the bottom-up approach to solution generation. And while this case study is situated within a collegiate context, this paper will conclude by projecting how this interdisciplinary material engagement can expand to an urban scale through institutions that already routinely democratize space and resources (such as the public library). To bring in the architectural models of pedagogy (and practice), and hybridize them with the production modalities of the engineer and entrepreneur, is to establish a new cross-modal and interdisciplinary approach that catalyzes bottom-up social change.

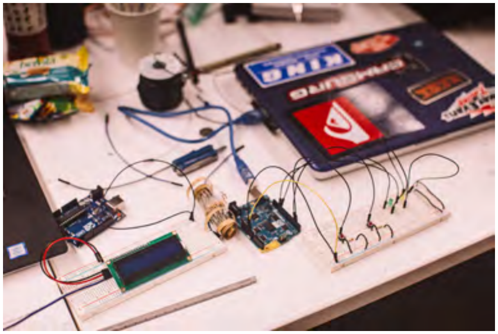


Figure 1
Photograph of typical physical computing prototype setup with Arduino microcontroller and other hardware. Photo credit: Michael Raspuzzi.

PHYSICAL COMPUTING + PROTOTYPING

By "physical computing" we mean active, physical systems that sense, compute, and then actuate using a variety of hardware components as coined by Tom Igoe and Dan O'Sullivan in their book of the same name (2004) nearly fifteen years ago as colleagues in the Interactive Telecommunications Program at New York University. Comprised of components like a microcontroller, sensors, motors and other actuators as shown in figure 1, physical computing also requires scripting skills in order to program the system and its behaviors. These systems require skills and knowledge that span multiple knowledge domains and disciplines, and in fact, the more sophisticated the system, the more complex the process of coordinating and integrating multiple disciplines in executing it (Vermillion 2014a). Given this, the process of building these systems is an opportunity for transdisciplinary pedagogies and practices based on a type of disciplinary 'pluralism' as discussed later in the paper.

Physical computing also reflects larger societal and business trends of collecting and aggregating data as inputs to making things responsive, smarter, automated, and/or autonomous. These days, enormous amounts of data are generated and collected daily and enormous amounts of capital are invested into finding ways to monetize this data. "Big Data" has become the primary catalyst for entrepreneurial innovations in our knowledge economy. These technology-based systems–whether disruptive or incremental–are transforming the built environment at various scales.

Cybernetic Cities + Autonomous Architectures

While Archigram's speculative Walking City project playfully pointed to a future of cities physically reconfiguring themselves as a collection of robotic buildings, our cities have always been cybernetic systems as articulated by Gordon Pask (1969). In other words, our urban environments have always been comprised of layers of complex, adaptable systems that are informed and adjusted by feedback loops, and these systems easily pre-date digital technologies. However, with the ubiquity of digital information and "smart" devices, municipalities are deploying cybernetic systems at the urban scale in the pursuit to become "Smart Cities." This framework of incrementally integrating data and cybernetics into our existing cities to optimize these urban systems has been made possible by the relative ease of collecting, sorting, and aggregating data via computing (Townsend 2014).

Kinetic or interactive architecture–being that there are multiple ways to name and classify (Achten 2011) architectural systems that can respond to data and change form (Schumacher et al. 2010)–are of a scale and complexity that make them relatively rare within our current built environment. So complex, in fact, that Chuck Hoberman claims that an architecture of change will require new theoretical and conceptual frameworks for design that span across a variety of disciplinary understandings (2015, 102). The need for new conceptual frameworks suggests rethinking teaching and learning in ways that, on the one hand, can span multiple disciplines with tasks that require divergent thinking, while on the other hand, can utilize each discipline's expertise to solve small, specific problems (convergent thinking) on the way to a satisfactory outcome.

Interactive Objects

With the urban and building scales in mind (but much too large to address), the "object" scale was chosen as a focus with more appropriate complexity for the make-a-thon prototyping via physical computing. Scaling back the complexity was especially important as most of the student participants had no experience with physical computing hardware or scripting and had to be brought up to speed very quickly while generating and refining ideas and prototypes in-situ. The object scale was also important in terms of student understanding–by thinking in terms of an object or device that could be plugged into the 'Internet of Things', or otherwise was interoperable with smart phones or other mobile devices and cloud computing, students could connect ideas to technology that they interact with on a routine basis.

PLURALISTIC PEDAGOGIES

The make-a-thon became a vehicle to test different strategies that would allow for a more pluralistic pedagogy that would combine design, engineering, and entrepreneurship. In order to scaffold the make-a-thon agenda, active learning methods were used, since these methods have shown to provide students with discipline-specific skills, but also life-long learning skills (Barrett 2010). As digital technologies have become mostly ubiquitous, they are also constantly changing and evolving and the authors feel that the ability to "learn how to learn" is paramount to sustaining a computational fluency for students throughout their academic and professional careers.

The case-study was conducted using a problem-based learning model. Problem-based learning involves immersing students in an open-ended problem, within which they can learn and apply discipline-specific skills while also learning and developing strategies and skills for the problem-solving process itself (Barrow 1996). This is a form of active learning in that students take responsibility for their own learning and obtaining or constructing new knowledge, usually in small teams. As learning is primarily self-directed, instruction is limited to scaffolding the design problem(s) to allow for students to cumulatively grow more self-reliant and instructors serve as guides and mentors to question or challenge the learning process (Schmidt et al. 2007). Additionally, a number of the following considerations, parameters, and constraints helped to shape the pedagogical outcomes of the make-a-thon.

Figure 2
Photograph of Arduino coding workshop over one afternoon during the make-a-thon. Photo credit: Michael Raspuzzi.

Purpose, Theme, and Timing

The make-a-thon agenda was structured and introduced around an open-ended provocation, framed as the "Future of Food." By using a universally understood topic we hoped to be inclusive of multiple, differing understandings, experiences, and rituals involving the harvesting, preparation, and consumption of food. And while the mentors and students discussed some larger, contemporary issues around food resources, the student team inquiries remained open-ended to be shaped by discussion and negotiation between team members during the ideation phase of the workshop. In doing so, the students were actively responsible for defining and constructing their own understandings of their project and the team-generated outcomes rather than passively receiving a problem to solve from tutors (Jonassen 1997).

Taking place over an intense three days and two evenings, the make-a-thon was programmed with a number of events to address and generate ideas, identify a variety of problems, and work on team-building. For instance, along with just work and tutoring time, skill-building tutorials and workshops (figure 2) were also included along with speaker presentations, group/team meetings, and meals.

Multi-disciplinary Collaborations

The make-a-thon was composed of 68 students from the University of Nevada Las Vegas. Sign-ups were voluntary and open on a first-come, first-serve basis in order to attract self-motivated student participants. While many different disciplinary majors from across the campus were represented, three categories were especially well represented in the student applicant pool–the design fields (architecture, landscape architecture, graphic design, sculpture), engineering and science (mechanical engineering, civil engineering, electrical engineering, computer science, mathematics, computer engineering), and business fields (entrepreneurship, finance, management and administration, etc).

The 68 students comprised 17 multi-disciplinary teams with 4 members each–the teams were composed with the goal of distributing disciplinary expertise throughout the team pools. Not to understate the significance of social interactions with team-based work, once teams were assigned, each member took personality and entrepreneurial core competency tests to better understand individual and team-based strengths and weaknesses. These steps were taken to try to ensure a successful shared/team work environment where everyone team member was valued and made important contributions to the final outcome. Importantly, this prepares students for working within teams based on diverse but complementary skill sets and knowledge (figure 3) in ways that are quick and temporal but also productive (Speaks 2006; Steele 2006).

Figure 3
Students worked in teams of four on parallel tasks Photo credit: Michael Raspuzzi.

Figure 4
Students giving final "pitch" presentation to judges. Photo credit: Michael Raspuzzi.

Iterative Prototyping Using the Arduino Platform

Physical prototyping materials such as cardboard, plastics, foam core, etc were provided for students as well as drawing supplies and cutting tools. The goal for each team was to start simple with the prototyping and build up complexity and sophistication in form-factor and behavior in an incremental fashion. In order to keep this process moving forward, workshops were conducted to cover topics such as problem mapping and ideation, arduino scripting and prototyping, design thinking, and making persuasive sales pitches.

As mentioned above, the primary microcon-

Figure 5
Examples of printed design and marketing information generated by each team. Photo credit: Michael Raspuzzi.

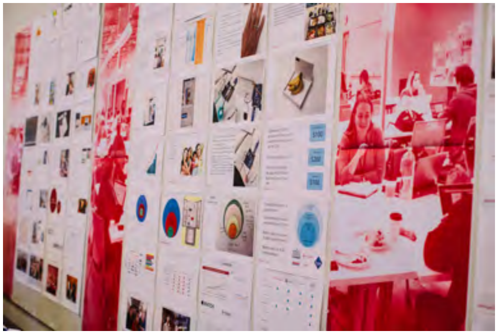
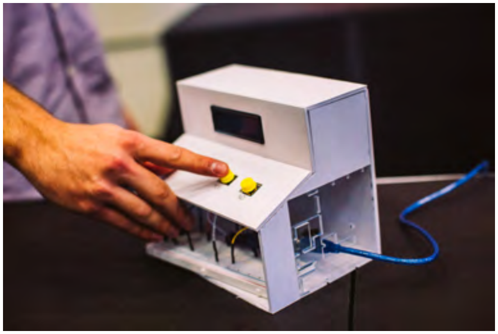


Figure 6
An example physical prototype in the development stage. Photo credit: Michael Raspuzzi.



troller platform used for the make-a-thon was Arduino. Arduino has a quite large and active user community that provides online resources for learning and testing ideas. This allowed for novice students to quickly learn the basics of prototyping a responsive system. Often, in the spirit of hacking, structured play (Schrage 1999), and other novel or unconventional ways of combining or re-appropriating existing technologies, the students would start with an already existing system and adapt it to a new purpose. In this way student learning was reinforced with assimilation and accommodation (Piaget 1950) to recall and combine prior knowledge with new knowledge in order to create something new or to modify something old in a novel way. Often in the ideation and prototyping processes, disparate concepts or tech-niques can be repurposed and combined to create something novel. For most students, "playing" with an Arduino and scripting was brand new and therefore a mistake-prone process that would sometimes lead to happy accidents. Discoveries or new combinations of technologies through their "mis-use" are nothing new to architecture, for example, Greg Lynn repurposing animation software like Maya to produce architectural propositions (Lynn 1999), or Gramazio and Kohler adapting flying quad-copter drones to stack masonry in precisely patterned configurations (Augugliaro et al. 2014).

Business Proposals and Pitch Competition as Incentives

In parallel with the prototype development, each team was required to develop a business pitch slide presentation in order to concisely present a persuasive value proposition to a target market. The Make-a-thon itself culminated with a juried pitch competition (figure 4). Rather than giving grades or course credits, the make-a-thon incentivized participation through awarded prizes and chances to spin off the prototype into a commercial venture with in-kind help donated by entrepreneurship organizations based off of the results of the pitch competition.

APPLICATION + RESULTS

Each make-a-thon team had a set of interconnected tasks to perform and products to deliver and these multimodal processes and deliverables presented opportunities for different paths and entry points into the process for each student based on interest and experience. For example, design and marketing information had to be produced (figure 5), physical prototypes were fabricated (figure 6) in tandem with developing a physical computing system to govern each prototype's behavior (figure 7), and an entrepreneurial "pitch deck" was developed to persuade judges about each idea's commercial viability (figure 8). The final resulting prototypes were photographed and publicly displayed after the pitch competition (figures 9-10) to demonstrate the accomplishments of each team with only three days of work.

The make-a-thon's pace was ambitious and much was learned about how to setup any similar events in the future. For instance, more tutorials and resources would need to be better front-loaded in the agenda in order to cover the skill-building workshops and give time for students to absorb and reapply the information. Another important aspect that was missing from this first version of the make-a-thon was getting the students to more formally reflect on their experience either through a townhall-style debriefing session, a journal, or a survey. Beyond closing the experiential learning loop, these feedback instruments could also lead to a better understanding by the organizers of what to adjust in future events.

Participatory Pluralism

Beyond a diverse array of fields or disciplines, the make-a-thon was also an attempt to measure a demographic pluralism–how inclusive and participatory could we make this event, particularly towards under-represented groups. Of the 68 student participants, 30 were female–a traditionally under-represented group in both architecture and technology-related fields (Doyle and Senske 2017). We hope to raise this ratio in future events.

Our university's demographics situate UNLV as the most racially diverse campus in the United States [1], yet our graduation rates are lower than they should be. We hope that make-a-thons and other similar programs can be catalysts for bringing students together in inclusive ways that spur productive exchanges and lead to understanding and empathy. We also hope that these events, which require our students to leverage their studies towards entrepreneurial ends helps to remind them of the value of their education, how it can be applied outside of academe, and looking beyond just a grade or university transcripts.

Figure 7
Development of physical computing behavioral system and integration with prototype.
Photo credit: Michael Raspuzzi.

Figure 8
A team giving their pitch deck presentation to competition judges.
Photo credit: Michael Raspuzzi.

CONCLUSIONS AND FURTHER TRAJECTORIES

For this first make-a-thon, the primary learning objectives were to: compare the role of the architect against that of the engineer and entrepreneur while exploring which tools are best suited for democratizing solution building; establish a methodology of cross-modal and interdisciplinary design practice through extracurricular events (such as the make-a-thon) while exploring innovative material engagement implications for teaching (and practicing) architecture; and explore how this prototype can expand to a larger scale while decentralizing the role of the future interdisciplinary architect. This project also radically collapsed, and therefore innovated, multiple disciplines into a hybridized condition that offered added flexibility and versatile adaptability in a number of contexts. And while this prototypical "make-a-thon" is situated as a short annual event, in the future we intend to coordinate similar events to build off of this initial program. We see this first step as an opportunity to build a community of designers and other professionals that are ready and eagerly engaged to jump up in scale to make our built environments responsive and "smarter." We see these make-a-thons as a precursor to this scaling up in size and complexity, similar to past examples of material and computing investigations from our past teaching that expand further into design studio pedagogy (Vermillion 2014b).

Figure 9
Finished prototype of a system that monitors plant growth and other vital parameters (light, humidity, etc). Photo credit: Michael Raspuzzi.

Figure 10
A final prototype for a smart attachment to a refrigerator that measures a user's biometrics. Photo credit: Michael Raspuzzi.

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[1] https://www.usnews.com/best-colleges/rankings/national-universities/campus-ethnic-diversity

Challenges - HISTORY AND FUTURE CAAD

The interfaces between technologies and the design process in AEC industry

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This is an exploratory study that had the purpose of understanding how Building Information Modeling (BIM), parametric design and digital fabrication are adopted in Architectural, Engineering and Construction (AEC) design processes and how they unfold through and influence its stages and activities. Questionnaires and interviews were performed with professionals from or with previous experiences in firms considered to be early adopters of digital technologies in practice. Results suggest that the addressed digital technologies have complementary functions and can improve each other's potentialities when integrated in design process' stages. Their performance can also be improved when achieving a more holistic process, embracing constant feedback loops through parties involved and design solutions throughout its stages. In order to have this approach in overall AEC industry, many transformations are needed and some of them were also pointed out in this study.

Keywords: *Digital Technologies, Design Process*

INTRODUCTION

Digital technologies, such as BIM, parametric modeling and digital fabrication, which are the subjects of this study, bring the computer as a much less neutral element than it was in Computer Aided Design (CAD) era, when it was adopted merely as a tool to reproduce manual work of representation (Aish and Bredella 2017). Differently from that, the computer now becomes an ally of designers in producing design solutions at the same time that it expands the possibilities not only for design exploration but also for production. This new, not only instrumental idea of digital contexts ends up demanding and provoking transformations to design process as well, once the latter becomes influenced by the new approaches to design process. To achieve a chain of automated processes from design to construction, reaching the possibilities of digital technologies in depth, it is necessary to make room for the ever-present interdisciplinary approach of construction industry in a holistic and non-fragmented manner and therefore to adopt non-fragmented processes (Bernstein 2012).

Although there are many publications about possible applications of each of these digital technologies in design process, the questions relate to how their applications are actually consolidated in professional practice and what are the interrelations between them within the procedural complexity that accompanies them. It is known that the absolute adoption of digital technologies in firms is more exception than rule in overall AEC industry, either because not all practitioners or firms have access to these technologies, or due to the resistance in adopting them. However, as Cross (2007) establishes about outstanding designers, experiences of early adopters, who instantiate the paradigm shift and often foster change in AEC industry, can give us projections on what to expect. This was the direction taken for the development of this study, that aims at understanding how digital technologies are used and the possible effects of their adoption in design processes' characteristics, based on different professionals' points of view.

METHODOLOGY

Data collection

Firstly, a review of publications was performed and allowed the authors to identify seventeen companies from different countries that outstand as early adopters of digital technologies. In general, these are global practices that usually work on larger scale and investment projects. Subsequently, through professional network and e-mail, professionals who work or have previous experiences in these companies were invited to participate by filling a semi-structured online questionnaire. More than two hundred professionals were contacted, however, only thirty provided responses that will be analyzed in this paper. According to preferences of some participants, the online questionnaire was replaced by videoconference interviews in their cases.

In order to compile different perspectives, no position criteria were applied on beforehand. The sampling strategies used were by accessibility or convenience (Gil 2008), as well as snowball sampling, since some participants indicated other professionals who could contribute to the study. Participants are based in different countries, but mainly European countries and the United States. Regarding their positions, there were: managers, project coordinators and BIM coordinators/managers (10), designers (8), architects (6), directors (5), engineers (3) and consultants (3), some of which simultaneously assume more than one function.

The design process definition adopted for this study, based on the definition by Fabricio (2002), involves all decisions and formulations aimed at subsidizing the creation and production of a project. Therefore, it is not only about the creative process from early design stages, it also includes the interdisciplinary design development, construction documentation, as well as construction and operation stages, which are subsidized by design decisions and sometimes require changes in them.

The questionnaire contains questions regarding the applications of BIM, parametric modeling and digital fabrication, as well as regarding the flow of activities developed in the stages of design process. These are: descriptive questions about the flow of design process, its stages and activities performed in each stage, software used and agents' involvement through process stages; plus three multiple choice questions about the main applications of BIM, parametric modeling and digital fabrication, respectively, with alternatives elaborated based on previous bibliographical studies about the use of technology in practice. In these questions, professionals could select more than one alternative for each and also provide additional comments through an "Others" section. Regarding the descriptive questions, in order to focus on the use of digital technologies in real world projects, participants were asked to provide responses considering the most digital design process they have ever been part of.

Qualitative analysis

The collected data were analyzed by using the Computer Aided Qualitative Data Analysis Software (CAQDAS) MAXQDA. The textual documents containing the questionnaire responses and the transcripts of the interviews conducted by videoconference went through coding in order to perform data reduction.

Codes related to the main thematic axes dealt with in the questionnaire were created: stages and flow of the design process; involved agents and their functions; software and their main applications; coordination, communication and sharing. Then, based on the individual analysis of each code's results, new sub categories were created in order to perform new coding rounds.

Stages were named in many different ways by the participants while describing them. Due do that, a design process reference model, elaborated based on the compilation of different bibliographical and documental sources (Melhado 1994; ABNT 1995; Tzortzopoulos 1999; AIA 2007; Succar 2009; Eastman et al. 2011; RIBA 2013), which could be compared to the descriptions provided by the participants, was used in order to organize the described activities in separate stages. Thus, the following division in eight stages was considered: Criteria and Constraints, Concept Design, Schematic Design, Design Development, Construction Documentation, Review and Bidding, Construction, and Operation.

Subcodes were also created for each software mentioned, for listed agents, activities related to coordination, and for the communication and sharing resources reported to be used. The analysis of co-occurrences and code frequencies made possible by CAQDAS provided new insights to the analysis and guided the presentation of the results.

Despite the variability of positions, companies and countries of the participants involved in this research, it is important to highlight that the authors analyzed the point of view of a restricted sample of professionals, which may not represent the majority on a global scale, given the limitations of the sampling techniques used. However, this is an exploratory study and its highlights are the fact that the discussions include diverse perspectives, from participants with origins in different parts of the world, as well as that it deals with BIM, parametric design and digital fabrication altogether and not separately.

RESULTS AND DISCUSSIONS

The contemporary design process

The summary of the design process' stages, containing the activities of each stage according to the descriptions provided by the participants, is presented in Figure 1. A strong presence of digital design methods and tools can be observed, which was expected, since participants were asked to describe the most digital process they have ever been part of, in order to focus on digital transformations.

Figure 1
Summary of descriptions of design process' stages and activities from responses.

According to the results presented, digital models can be considered central artifacts of design activities, that guide decision-making and are progressively being developed over the stages, acquiring new information and becoming increasingly detailed and complex at the same time. Despite this, it is important to highlight that digital methods and tools are not necessarily completely substituting traditional ones, since sketches and diagrams, for example, still play a significant role in design activity (see Figure 1). Physical models were used for a long time in design process and still are, but now they can be produced by digital fabrication methods. Therefore, what happens in the contemporary design process is an evolution and integration of different methods that complement each other and open up new possibilities to meet the growing demands of AEC industry, which are, simultaneously, according to Deutsch (2017): speed, feasibility and quality.

This leads us to two different issues that have to be remarked. First, this whole context of digital tools and features eventually brings challenges to designers in overall AEC industry regarding the necessity of developing new skills and competencies, including and especially ones related to the management of the expressive amount of data that is now generated through digital design technologies. At the same time, everything needs to be integrated so that this complex contemporary design process works efficiently. In this sense, the traditionally high levels of fragmentation between activities and products from different design disciplines in overall AEC industry are becoming impractical and unfeasible.

The design of a building was not ever simple. Buildings are complex structures, composed by many different disciplines and elements. Add a whole new world of artifacts and embedded design data to this already great complexity. It becomes clear that transformations in design process are needed in order for that to work properly. This complex context that accompanies digital technologies may be routine in some global AEC firms (the early adopters), but in the rest of the industry, it can be extremely confusing and even detrimental to their productivity and results.

Regarding the need for integration in different facets of design process, other results of this study should be analyzed. Participants reported to have observed different ways of conducing the design process in practice, with several forms of negotiations between parties involved in order to incorporate feedbacks to design solutions along design process' stages.

As one of these possibilities, some of them mentioned the pre-establishment of milestones before the beginning of the project to forecast breakpoints and reviews in order to incorporate feedbacks from others involved, conditioned to the approval of certain parties. The main functions of these predetermined loops were reported to be related to review of issues such as constructability, cost, efficiency, coordination, performance of the project and the means of production. According to the respondents, in addition to these items of technical and economic bias, feedback is primarily intended to incorporate the opinion of the client/owner and to get their approval. Many of them also highlighted that a participative behavior of the client during design process is extremely important to project results.

The prediction of breaking points in process' stages for clients or other designers' reviews does not necessarily imply an effective and ideal integration. However, more integrated and iterative approaches of conducing design process were also reported, referring to the constant analysis of previously mentioned aspects (such as constructability and costs) since early concept design stages, in order to optimize design solutions and reduce possible problems and rework. In these cases, digital technologies were pointed out by the participants as playing a fundamental role for enabling and fomenting these iterations, considering its simulation and optimization features, as well as the possibilities of having more transparent flows of data. However, they also pointed out the difficulties in changing other parties' mindset to this open information approach, some of which were presented in a previous publication of early results of this research project (Zardo and Mussi 2018).

Also, some participants mentioned that the type of contract can limit or extend designers' involvement in a project. This inevitably will influence their comprehension of what the design process embraces, which tends to cover the main stages they participate in. Therefore, in line with the need for greater integration in contemporary design process, giving space to more flexible and integrative types of contract can help in reducing the procedural complexity that hinders the insertion of technology in most of AEC firms.

As it's possible to see in Figure 1, operation stage was only briefly described by participants and no mention was made to the use of digital technologies at this point, although there are many publications about post-occupancy evaluation and facilities management with the use of digital models in academia. This may have been due to the fact that this stage is sometimes not embedded in designers' belief of what the design process encompasses, but also suggests that this needs to be further explored to complete the cycle of digital technologies and for not only designers but also users to achieve all of its possibilities.

Tools and technologies in design process' stages

The increasing complexity of the contemporary AEC design process extends to the amount of tools available. In terms of software, a myriad of products were listed by the participants. There is a whole ecosystem of them related to BIM, parametric design and digital fabrication available for building designers, with complementary functions, so not only are there many available, but many are used for the same project. Holzer (2015) also reports how different tools are progressively converging in architectural design studio, focusing on the relationships between geometric exploration and building performance, which is just one of the many examples of how integrating different tools can improve design solutions. The main software reported by professionals are, according to their different categories of applications:

Sharing Data, Communicating, Managing Information and Tasks: New Forma, A360/BIM 360, Bluebeam RevU, Aconex, Teamwork Projects, Trimble Connect, Athena, ProjectWise.

3D Modeling: Rhinoceros, SketchUp, Maya, Geomagic, Zbrush.

Parametric Modeling and Visual Programming: Rhinoceros, Grasshopper, Maya and Dynamo.

Presentation/Visualization: Rhinoceros, SketchUp, 3Ds Max, Illustrator, Enscape, Adobe Suite, Photoshop, Lumion, Maya, Powerpoint, InDesign and Navisworks.

BIM Modeling: Revit, ArchiCAD, Tekla, Vectorworks, Digital Project.

Coordination: Revit, Navisworks and ArchiCAD.

Specification, Documentation, Detailings, 4D Planning and Fabrication: Vectorworks, ArchiCAD, NBS Create, Tekla, Microstation, Digital Project, Grasshopper, Excel, Revit, Rhinoceros, Synchro, CADMEP, Word and AutoCAD.

Programming: Visual Studio.

Simulations and Analysis: Revit, Grasshopper and InfoGraph GmbH.

Rationalization: Rhinoceros and Grasshopper.

Nevertheless, the possibilities become so broad in computational design that sometimes commercial products don't even contemplate functions needed by designers, which demand customized solutions, usually developed through scripting, another new skill that wasn't usually part of traditional design activities and that was also reported by participants (see descriptions of stages 4 and 5 in Figure 1). Moreover, as presented before, tools that were not even created specifically for AEC are being inserted in buildings' design process, such as Maya or Visual Studio, which means designers' scope is expanding with this interdisciplinary digital context.

However, considering that integration in AEC projects is an eminent necessity, this whole ecosystem of tools has to be made easily interoperable in order for many stakeholders to collaborate through different computational design activities, but this is still a hard task. This points out to the needs for improving interoperability in (not only specific) AEC software and highlights why this is a recurrent object of study in publications from the field of CAD.

From a broader perspective, regarding BIM, parametric design and digital fabrication in design process, Figure 2 presents the stages of design process and their presence along them, according to the descriptions of activities, as well as of the main software previously mentioned, organized by order of frequency in responses, which means digital repositories were mentioned the most, followed by Rhinoceros, Revit and so on. Although as built models were reported to be developed using BIM, their use after construction stage was not specified, nor of parametric modeling or digital fabrication.

One important first aspect to be discussed about Figure 2 is the concurrent presence of BIM, parametric design and digital fabrication in most design process stages, which suggest an overlapping/complementary relationship among them. This becomes clearer when analyzing the applications reported by professionals for the three technologies considered in this study, presented in Figure 3, as follows.

Main applications of digital technologies

Besides the ones in Figure 3, professionals also cited as BIM applications: 2D documentation production, project visualizations, and safety analysis. As for parametric modeling, the additional applications are: development of custom tools and BIM objects, and analysis of code/law requirements. There were no additional applications for digital fabrication besides the ones provided in the question.

Regarding the main applications of BIM, it is mainly related to activities from design development and construction documentation stages, such as project coordination, quantities and cost analysis, which are compatible with its strong presence reported for those stages and suggest that BIM is usually inserted in design process after having a well stablished concept design.

However, its third main application according to the respondents (geometric exploration) draws attention for being an activity essentially performed in greater depth during early stages of design process.

There are many discussions about using BIM in concept design stages in publications and presentations, from those that present favorable arguments, such as Garber (2014), to those who discuss its limitations for this purpose. Some limitations, pointed

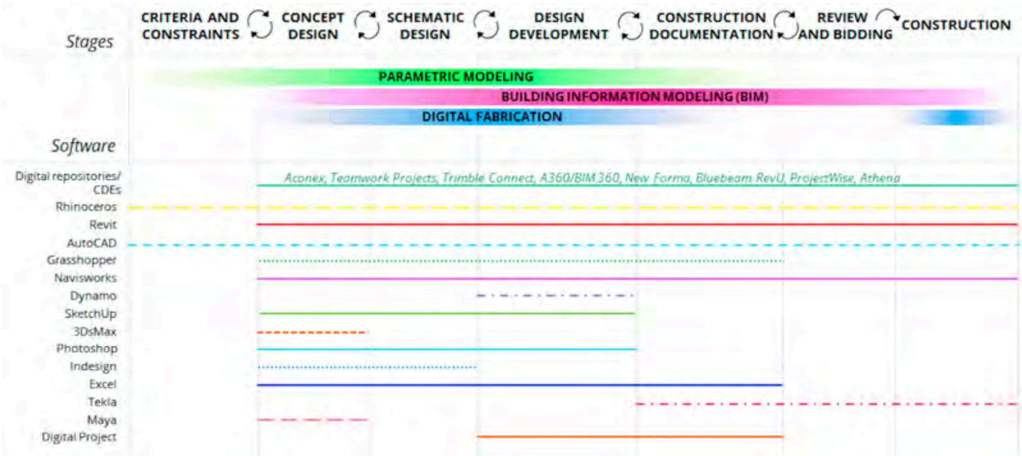

Figure 2
Presence of BIM, parametric modeling and digital fabrication, as well as of the main software pointed out by participants in design process' stages.

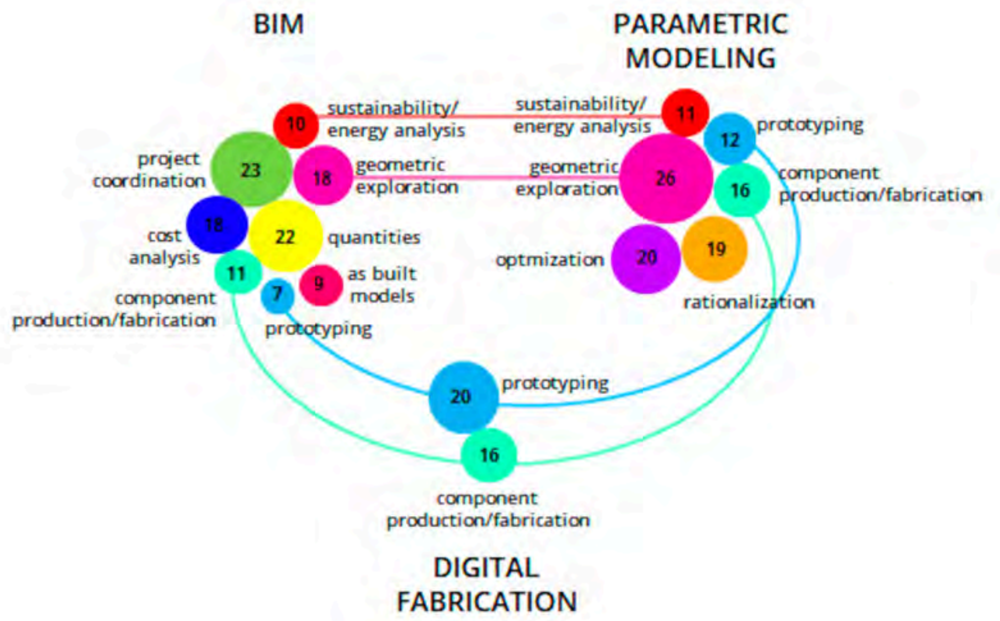

Figure 3
Main applications of digital technologies in design process. Circles show the frequency of each application in responses.

out by Robert Aish [1], can be cited as examples, such as the need for thinking in micro ideas (components) before macro ideas (general design solution); the need for precision in BIM models, which is not necessary yet in conceptual stages, when there are still some uncertainties; and the risks of BIM software inhibiting exploration due to the rigidity of information models.

The significant use of BIM for geometric exploration reported may be related to the fact that, in contemporary and digital design processes, analysis of real building data, in attributes of BIM models, are being included in concept design stage. In order for this process of simultaneous geometric exploration and analysis of accurate data to occur, it is necessary to give space for the previously mentioned iterations during the development of design process' activities.

It also should be noted that geometric exploration was reported to be the main application of parametric modeling. This and the other correspondent activities to both technologies support the argument that they complement each other and overlap in the midst of design process. This idea is reinforced by the relationship that can be established between optimization and rationalization, developed through parametric modeling software, and the analysis/simulations based on real characteristics of a building or site in its digital prototype, made possible by compiling BIM models with data attributes and features of parametric modeling tools. Besides that, respondents also mentioned the growing development of customized tools and BIM libraries through visual programming, suggesting that simultaneous adoption may be more appropriate than punctual applications, since one technology can help improving or managing the other.

When it comes to digital fabrication, the situation is similar. Both BIM and parametric modeling have the production of components and prototyping as two of their main applications. So, when combined with digital fabrication, they can allow the development of file-to-factory processes as well as early materialization as a resource for studying design solutions, reducing significantly the historical gap between design and production.

According to the respondents, prototypes are also commonly used to communicate ideas to clients as a visualization resource. The predominance of prototyping over component production may be related to some requirements that are not common in the overall AEC industry, such as millimeter precision in digital models and strict planning of transport and assembly processes, as Scheurer (2012) points out, other aspects that should be reviewed while adopting digital technologies, especially in the case digital fabrication.

In summary, it is possible to argue that the benefits of using digital technologies in design process could be enhanced by their joint adoption. This is not to say that, individually, they do not present benefits. However, joint adoption opens up a new range of potentialities. The process also becomes more holistic since it's not just about adopting a new tool to accomplish a specific objective but about adopting a whole new dynamic that is required to an integrated design process. In this sense, the convergence of technologies ends up reflecting in other aspects of design process, that also start converging. Deutsch (2017) describes this as the convergence era. However, challenges related to the necessary changes are of proportional size, which explains why punctual adoptions of digital technologies predominate in the sector over this ideal holistic process.

Shifts, contrasts and challenges

Design and production, which present a historical gap, with origins in the use of drawings as the main design and documentation feature (Mitchell and McCollough 1995), are becoming closer due to technology. Using digital models that are much clearer to production and construction processes and also using digital fabrication to analyze different materials or to analyze design solutions in different scales, as well as to produce real scale components for onsite assembly inevitably reduces the gap, which reflects in an approximation of design-specific tasks to construction. Due to this, digital technologies not only affect design but also construction and have the potential to affect operation as a result of an overlapping effect in design process' stages.

Moreover, when asked about the agents' involvement, many of the participants said that the design team becomes engaged with contractors during construction and that contractors and subcontractors have active participation in elaborating design details and specifications, so the roles of those involved also start to merge at some point. This contrasts a lot with fragmented processes that are predominant in a huge part of the sector globally, and is possibly a reflex of the adoption of digital methods in AEC industry. As pointed out before, new design methods and technologies make it easier and more feasible to integrate parties and activities.

This integration is accentuated by the use of digital repositories while designing and building a project, or Common Data Environments (CDEs), which are even contemplated in building codes and regulations in the United Kingdom. It is important to highlight that these are not substituting traditional means of communication, such as e-mail or meetings, which were also strongly mentioned in the responses obtained. However, despite many different commercial platforms for this, these repositories allow the parties involved in a project to organize and manage all of the information that is generated through digital technologies, as well as improve the collaboration and communication between stakeholders, thus generating optimized design solutions and project results, so they mark a significant transformation on the way parties relate to each other during design process.

However, reinforcing what was highlighted by participants, there are many challenges to this new dynamic of design process. Besides the new competencies and skills previously mentioned, collaborative thinking, motivation to integrate and share design information (with other designers, consultants and contractors, for example) are extremely important aspects which are not easy to achieve. Regulations such as the ones developed by NBS in the UK also play a fundamental role to organize and make it feasible and accessible to other firms that don't have the flexibility that global practices usually have.

Regarding this, it becomes relevant to highlight that the responses from British participants were highly similar for describing the development of the design process, since most of them follow the same references from RIBA in practice. Having the majority of firms in a country following a similar protocol could make it easier to integrate digital technologies and manage their respective effects in design process thoroughly.

There are many firms and professionals involved in any larger scale project, including ones based in different geographical locations. The understanding of the design process still varies a lot from different localities and different companies, which was already expected in the results of this study, since it involves professionals from many firms and countries. This can make integration and holistic processes a lot harder to achieve. However, when having the same patterns from building regulations being followed at a larger scale than one country, and the support of shared repositories, some of these issues could be more easily handled and strategies could be more easily planned and implemented.

As mentioned before, rigid types of contract also aggravate this scenario. So, besides promoting the development of adequate regulations, bringing flexibility to rooted contract types used could help, giving space to new approaches such as Integrated Project Delivery (IPD), which can form an access road to the holistic design process fostered by the possibilities of digital technologies.

In Brazil, regulations are highly limited and in its initial steps, while fragmentation of design processes, hierarchical work settings and rigid contract configurations still predominate in AEC industry. Also, in general Brazilian AEC industry, even though digital technologies are being gradually inserted in design process, it is in an isolated or punctual manner, not compatible with the processes and possibilities found in the presented results. There are exceptions indeed but the vast majority can fit this scenario. So, in this study, evidences that show the contrast of different realities could be collected in order to highlight and disseminate the need for change in many aspects of the AEC sector.

Although the digital and holistic design process presented along this study is still very restrict to some exceptions worldwide, the results show that there is a reason for that. By changing mindsets, investments, organizations, contracts and teaching it could be possible for it to be expanded in global AEC industry, concurrently to the integrated adoption of BIM, parametric modeling and digital fabrication.

However, process complexity is probably going to grow even more in the next few years, considering that there are other emergent technologies that weren't even subjects of this study, such as Virtual Reality (VR) and Artificial Intelligence (AI), that bring other new possibilities as well as change the way people communicate and operate. Thus, extending the compilation of digital technologies to include the emergent ones can further enhance integration in design process, since they can offer other complementary potentialities to the ones approached in this study.

Therefore, understanding the new dynamics that come with the adoption of digital technologies has to be a constant effort from academia, but it also has to be extended to practice, otherwise they will keep being adopted as mere instruments for punctual functions that don't effectively justify the investments of money and time. Understanding how they unfold through and influence design process' stages can help guiding the major part of AEC sector in this technological insertion trajectory.

CONCLUSION

The results, in summary, suggest and reinforce the idea that digital technologies can drive and intensify the iterations and integration of activities developed during design stages. One of the main conclusions is that technology needs to be used simultaneously and in holistic and integrated processes, as the fragmented adoption tends to maintains the gaps and inefficiencies of fragmented processes, requiring additional efforts that may not be fully compensated in terms of immediate benefits to project results.

However, many changes are needed in order for that to happen smoothly, which are mostly very hard to achieve. This includes changes in the mindsets and way of working by professionals and firms, changes in contracts, promoting patterns for using and integrating so many different technologies, as well as inserting new skills to be developed for future AEC professionals. The lack of these are the possible reasons why digital technologies are commonly misadopted in AEC firms, so understanding how they unfold through process stages is an effort that is needed not only from researches but also in practice.

In the age of the 4th industrial revolution, the emergence of new features each day will probably elevate process complexity, leading to the compilation of already disseminated technologies to emerging resources, expanding practice's scope a lot further. This emphasizes the importance of both disseminating this integrated digital ecosystem beyond early adopters and understanding and being able to deal with the relationships in the interfaces that develop between them and the design process.

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Reprogramming Practice

Revising design thinking through digital fabrication

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Questioning the importance and impact of design thinking methodologies in the architectural design studios is a backbone of architectural education in twenty first century. 3D printing and digital manufacturing are disruptive technologies that are changing architects and designers daily lives. These trends require new skills, based on a deep understanding of digital continuum from design to production, from generation to fabrication. This continuity transcends the merely instrumental contributions of a person-machine relationship to praxis, has begun to evolve as a medium that supports a continuous logic of design thinking and making. Design thinking methodologies associated with digital fabrication emerged as a leading technological and design issue of digital research and design. As designers, we are witnessing a no frontier between computational design and digital fabrication. For this paper is taken into consideration the work of two architecture studios that share a unique background on new methodologies by embracing the digital technology in their own practice. Their work reflects on new design methodologies facing the expansion of digital technology in architectural practice. This paper discusses the possibility of new design thinking methods driven by digital fabrication.

Keywords: *Design thinking, Digital Fabrication, AEC, Collaborative Design, Architectural Practice*

INTRODUCTION

Technology advancements have a profound impact on design thinking in architecture, professional practice and architectural education. Computational design thinking (Leach & Yaun, 2017) and innovative approaches in digital fabrication bring new demands for rethinking of architectural practice (Morell, 2015; Dye & Samuel, 2015; Hensel & Nilsson, 2016; Aksamija, 2016). Only an inclusive approach can engender the understanding required to address the many issues raised by the fourth industrial revolution. This will require collaborative and flexible structures that reflect the integration of various ecosystems and which take fully into account all stakeholders (Schwab, 2016).

The Architecture, Engineering and Construction

Figure 1
Left – Digital Crafting Collection, 2012, gt2P; Right-Lexus design award 2018: DIGITALAB's generative system links low-tech materials and high-tech processes.

industry is in a state of flux fueled by transformative shifts in technology and design (Menges et al, 2017). Financial incentives around new economics of production, increased efficiencies afforded by streamlined communication and the automation of labor-intensive processes are already underway (Corser, 2010; Gramazio & Kohler, 2014; Bernstein & Deamer, 2010).

In this context, the architects have a momentary opportunity to give a direction to this shift that will set the foundation for the next generation of architects.

Technology research should not be bound by constricting disciplinary standards, constrains or ideologies lest we limit its potential. Yet to explore this unprecedented potential requires not only a technical grasp of digital fabrications' capabilities and limitations, but also an in-depth understanding of the disciplinary consequences of technology research.

The rise of design thinking has to do with a greater understanding of the methods and process developed in the design (Cross, 1984). Processes have been established (analysis -> ideation -> prototype -> iteration -> implementation), and tools have been defined (brainstorming, rapid prototyping, desktop walkthrough...) in order to transmit and generate truly collective processes.

This deeper understanding has led to an explosion of applications and a broader collaborative process. One of the major principles in design thinking is that the process is constantly changing: it never repeats systematically, and we must be actively creative with the process itself (Rowe, 1987).

If architecture follows the path which the design has begun, then it will produce a wide range of improvements and modifications in both directions.

Architecture is facing problems or situations in which a plastical, formal or spatial approach is not enough; we must improve and adapt the tools and processes to approach creatively different issues. On the other hand, the act of participating and creating design processes from the architectural knowledge enables to introduce new tools in the processes.

The design thinking model extends its tools and methods that came essentially from product design, user experience, design services, among others, and architecture can face problems with a holistic approach, allowing architects to act in situations which previously were unknown (Menges, 2011).

Design thinking promotes a human-centered and an open-ended approach, seeing failure not as a mistake, but as an opportunity to learn (Makstutis, 2018). As Penn (2015) argues architectural professional practice is a body of knowledge in part the result of training, but is largely a result of practical experience. It comprises both explicit and tacit knowledge - learned not through theory, but through a process of reflection on experience; by watching others, and trial and error, coupled to actively thinking about why some things worked well and others failed.

IDEO (product design) and OMA/AMO (architecture) are large structures with many types of projects, both have depth in an intense way in the creative process and have reached a similar conclusion: the creative processes of design (especially collective) are applicable to a variety of situations, even in antagonistic disciplines such as politics, management, marketing, etc. (Cross, 2008).

In this context, the subject of this study is the necessity, importance and impact of the design thinking methodologies, which plays a complementary role rather than support in the architectural design studios which is a backbone of architectural education (Burry et al. 2010; Wagner et al 2010; Wiertelarz, 2016; Gu & Wang, 2012).

For this paper is taken in consideration the work of two young architecture studios that share a unique background on new methodologies by embracing the digital technology in their own practice. Their work reflects on new design methodologies facing the expansion of digital technology in architectural practice. This paper explores the possibility of new design thinking methods driven by digital fabrication.

The outcome of this study, results in a taxonomy projecting a new design thinking process based on the methodologies adopted by the architecture studios in study. This preliminary taxonomy presents a new concept where digital fabrication is the common aspect along the design process, performing as support and an integrated aspect of the process.

METHODODOLOGY

The study adopted a methodology to reveal possible new design thinking methods driven by digital fabrication based on the analysis of the work of two architecture studios.

Both young studios were selected to enroll in this study due to their work developed in the practical context that is expanding traditions of making towards new techniques that integrate manual craft, computational design, digital fabrication, and advanced robotic technologies, often in hybrid relationships. The two studios in study in this research support this concept.

DIGITALAB and gt2P are architecture studios “born” in the digital environment and are dedicated to explore digital design and fabrication, or as they call themselves: they are digital crafters (domusweb, 2018) (dezeen, 2019) (figure 1). They both focus their work on the continuous process of research and experimentation in digital crafting, promoting new encounters between the technologies for projecting and the richness of the local expressed in traditional materials and techniques. With digital fabrication, they were able to turn the attention to the physical nature of architecture, by opening up new aesthetics and functional perspectives and address the digital in architecture as a radically contemporary building culture.

DIGITALAB is a Portuguese multidisciplinary architectural office, creative lab and design studio, focused on both generative design and digital fabrication, by merging analog and digital technology in order to come up with computationally generated designs and structures. It is a young practice led by Ana Fonseca and Brimet Silva that develops projects in several fields: product design, art installation, interior design, architecture and digital research. DIGITALAB is committed to employing new technologies in the production of forms and spaces, exploring strategic combinations between generative processes (Computational design) and digital fabrication technologies (3D printing, CNC, laser-cutting, and robotics). Their main goal is to explore the potential of digi-

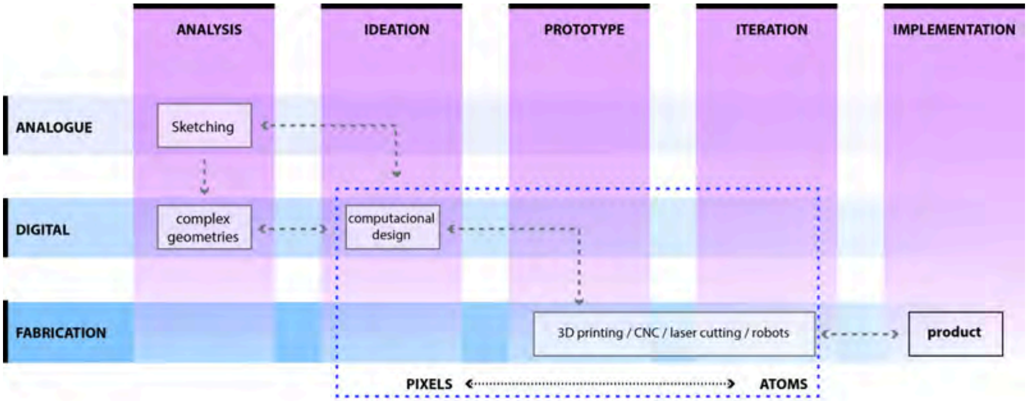


Figure 2
DIGITALAB
workflow diagram

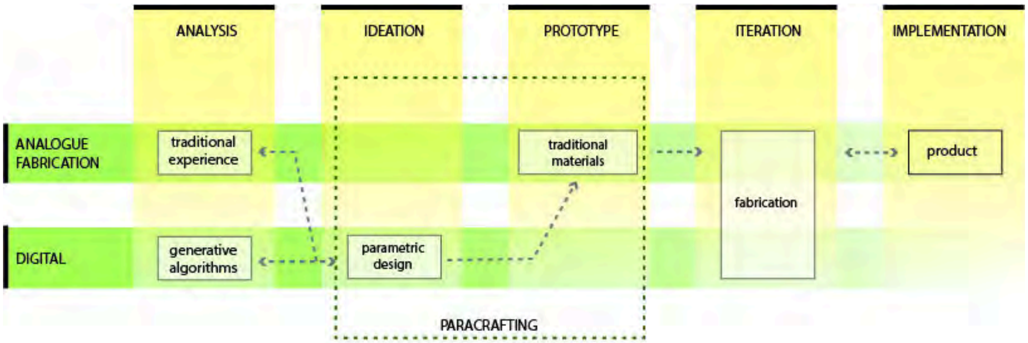


Figure 3
gt2P workflow
diagram

tal tools as creative weapons to transform pixels into atoms, and virtual processes into physical objects and environments.

Gt2P - Great things to People is a Chilean collective involved in projects of architecture, art and design and with an experimental approach that combines digital fabrication, traditional craft and materials. They are driven both by their cultural heritage as well as a dedication to parametric design, or paracrafting - wherein they devise physical production systems and then play with variables within those systems (such as time, temperature, volume, etc.) to manipulate materials in unexpected ways.

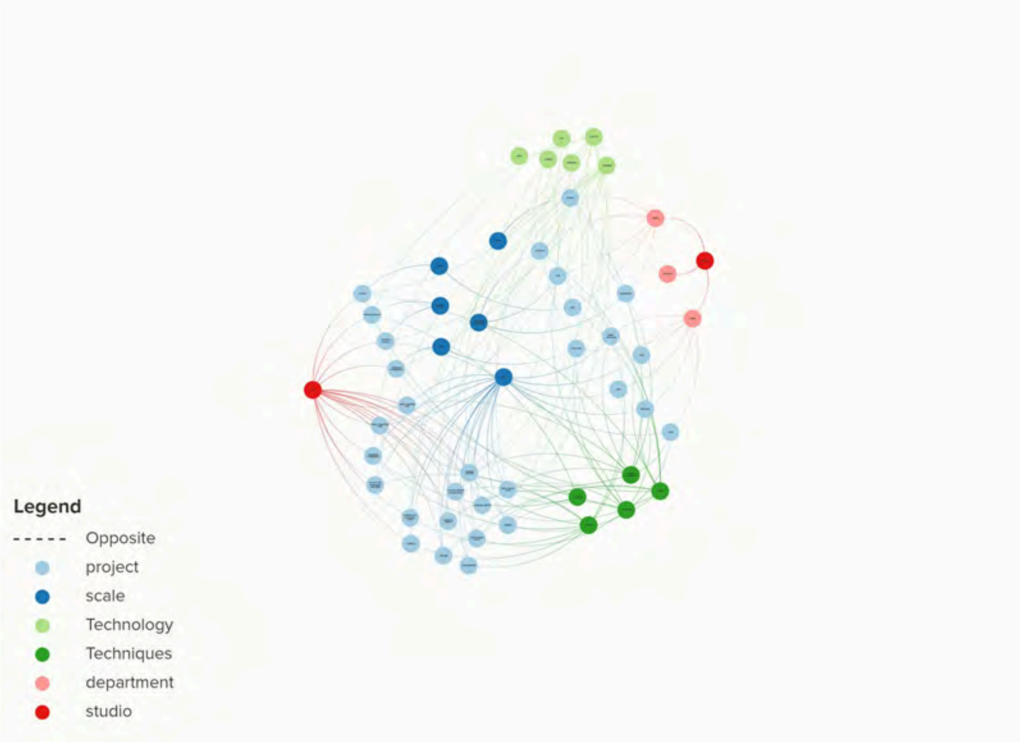
The taxonomy design encompassed 2 stages: (1) getting inspired - analyses the studios workflow and online interviews; (2) Learning by doing - analyses a group of projects of each studio.

GETTING INSPIRED

The first analysis is based on the studios workflow, and as a result, we produced two diagrams explaining the processes of each office.

DIGITALAB is organized in three major departments: form, space and research, being each one of

Figure 4
Preliminary taxonomy relating DIGITALAB with gt2P group of projects



them focused on different scales but they all share a common interest: employing new technologies in the production of forms and spaces, exploring strategic combinations between generative processes and digital fabrication technologies (figure 2).

Their workflow is based on the idea that pixels become atoms, meaning that from matter and materials, comes materialization. Starting from the sketch they develop the concept and test it on the digital environment with the support of complex geometries and computational design. From there it starts the process of developing the final product between generative design and the implementation of digital fabrication. It then allows to explore materials and processes until the final result.

Gt2P refers to their approach as paracrafting. This is the way that the studio experiment with parametric design, focusing on production processes that often incorporate analog fabrication as well as traditional materials. This frees parametric design from its usual connection to computers and it contextualizes their work within the national landscape and culture. This way of systemizing ideas and processes through variables also allows them to create entire object families, rather than isolated objects.

Their work methodology has two dimensions (figure 3). First, they seek to systematize knowledge and observation, whether of natural, artificial, geometric or spatial, phenomena, through generative algorithms. Here parametric design is a tool to guide the planning of projects that they carry out, enabling the integration of its stages of design, development and production. Their workflow bounces between the analogue and the digital supporting each other along the design process.

On the other hand, they have discovered an artistic dimension that connects them with their cultural heritage, through the incorporation of traditional experience and knowledge that feed and qualify the generative algorithms or DNA that they create. At the end, they expose the unexpectedness of manual processes and local materials as a way to value what they are in what they do.

LEARNING BY DOING

To support this investigation, it was taken in consideration several projects from each studio: from DIGITALAB were taken as a reference eleven projects dated from 2015 to 2019; regarding gt2p, we had as reference nineteen projects developed from 2010 to 2019. As criteria we took into consideration 4 parameters: scale, processes, tools, and craft vs. digital.

We took into consideration the scale of projects (if it's an objects, a building, a system or a temporary structure), the used techniques (complex geometries, folding, tessellation, forming, sectioning), the tools or the technology used to develop the projects (traditional techniques, laser cut, CNC, addition or robots) and even comparing the use of crafts or the digital environment in the projects.

To help us organize and visualize the information in study, we used Kumu as a tool to produce a relationship map (figure 4).

This preliminary taxonomy presents a new concept were digital fabrication is the common aspect along the design process, performing as support and an integrated aspect of the process.

Looking over the data collected, it is clear to state that both studios take digital fabrication as an opportunity to explore further and complement the crafts potential. The range of projects in analyses shows that they work in different scales, and with time they have found a way to make design work as a business. They have realized that it is in diversity where their real value or contribution is by breaking boundaries in practice and by combining symbiotic techniques.

The produced design thinking diagram helps the main investigation by understanding and supporting the belief that digital fabrication is not only a tool, but rather an integrated strategy in collaborative digital processes that can allow a better communication along the design process.

By analyzing and evaluating the work achieved by these two studios, we can relate and comprehend how two independent offices have been developing their unique way of working and thinking with the support of digital technologies.

There is no doubt that the profession is expanding traditions of making towards new techniques. It is clear in their work that digital fabrication is a technology used not only as a tool to produce the final piece, but mostly a way of thinking that supports the entire process along the design thinking process.

DISCUSSION

In this paper we argue that design thinking in the architecture studio may benefit from digital fabrication, to foster a more profound understanding of these processes among architects. Digital fabrication is being coalesced in design studios in order to optimize the traditional workflows they're already familiar with. This technology doesn't necessarily replace the existing tools, when implemented well it simply evolves existing workflows.

This paper is part of a study that investigates the architectural design process and starts from the premise that we should expand the study of design methods to include other approaches. It considers digital fabrication not only as a tool, but as an integrated strategy in collaborative digital processes that can allow a better communication along the design process. It presents the development of design methodologies in order to contribute to a greater understanding of the methodology for design projects with caution to the fact that each one reflects the period in which it was developed.

The emergence of complex technological and environmental problems, challenge the professionals to seek novel practices of collaboration and exchange that deliberately overcome and dissolve traditional disciplinary boundaries. This collective approach to working with technology is not only revolutionizing how things are designed and made, but is fundamentally transforming the culture, politics and economics of the creative industries as a whole.

If the first robotic age - the age of industrial automation - vastly improved our physical productivity, the second robotic age will surely come to distinguish itself as a driver of creative capacity. The present moment is ripe for connecting technology with imagination and materialization, inspiring new fundamental discoveries and opening new scientific frontiers.

Based on the work produced by DIGITALAB and gt2P we can understand how digital fabrication enables new relations and allows a high-tech and low-tech approach where craftsman practices is mixed in with technological processes.

The development of a preliminary taxonomy allow understanding the role of digital fabrication on design process in architectural practice along with a discussion of their capacity to question the basis of education and the conceptualization of architecture.

CONCLUSION

This paper intends to discuss the relationship between making process in design-led research and other aspects that are challenging architectural practice.

Design thinking methodologies associated with digital fabrication emerged as a leading technological and design issue of digital research and design.

Integrating digital fabrication into design thinking contexts is by no means a straightforward process. This study reveals that design thinking in the design studio can benefit from digital fabrication as an integrated part of the work setup. Design thinking supports the studio work, in which failure, iterative processes, and continuous reflections on fabrication materials are integral parts of the process. Our observational studies, design thinking theory, and research experiment accounted for in the paper set out a trajectory for more thorough studies of how design thinking may be integrated into creative and reflective processes of digital fabrication in the design studio.

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Digital Expansion of Stereotomy

A semantic classification

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This paper presents a critical analysis and reflection on stereotomy with the purpose of updating its theoretical discourse. Having risen to the apex of architecture technological possibilities in the 17th century, stereotomic construction lost its importance in favour of iron, steel and other materials and construction techniques brought by the Industrial Revolution. More recently, much owing to the possibilities offered by digital technologies, a resurgence of interest in the subject has spawned various researches which bring stereotomy back to the architectural discourse. Although technological applications and design innovations in service of stereotomy have developed in multiple interesting paths, there is a lack of a common theory on the subject which is capable of relating these multiple apparently diverging stereotomic approaches between each other and, maybe even more importantly, to the classical practice which sparked the development this discipline. The research presented in this paper shows how the digital tools were instrumental in bringing this tradition to architecture contemporaneity and how a current stereotomy is largely supported by these technologies, while keeping strong relations to its classic origin.

Keywords: *stereotomy, classification, history, digital*

1. FROM CLASSIC TO CONTEMPORARY STEREOTOMY

Carefully cut stone for spanning spaces is first found in Greece, and later heavily used by Romans. Complex vaults of gothic cathedrals were possible due to the masons knowledge of cutting stone in the correct angles, often shrouded in mystery. The humanist Renaissance spirit of gathering knowledge and disseminating it to empower human endeavour is all present in Philibert de l'Orme's Le premier Tome de l'Architecture (de l'Orme 1567); this book contains in its Livre III the first comprehensive treaty in the subject of coupe des piérres, a field of knowledge still not known as Stereotomy at the time. De l'Orme was interested in bringing the art of cutting stone out of the exclusive practitioners, the masons, into the creative act of the architect.

De l'Orme's treaty was soon to be followed by many others, revealing a keen interest in the subject by the architecture elite. The beginnings of stereotomy saw the discipline be developed and taught along side others such as geometry, optics or statics, revealing its wide scope of relations. This allowed for multiple innovations present in the treatises on stereotomy, namely the seminal engineering statics to be developed in the treaty of de La Hire, projective geometry to be inaugurated by Desargues, or the ubiquitous descriptive geometry in the teachings of Monge.

The development of stereotomy alongside descriptive geometry was contemporary to the beginnings of the Industrial Revolution, and the new double orthogonal projection found perfect suitability for describing machines and parts for production. Iron and steel soon became cheaper and solutions based in metallic beams and trusses became more common than cut stone structures. This caused a slow but steady fading of this classic construction technique.

The maturity of the Industrial Revolution developed a more productive and precise fabrication, providing a wide range of mass produced systems. A finer control of production allowed for more accessible accurate machinery, eventually assisting the development of the computer. Its development into programmable machines accessible by professionals such as architects sparked in the 1990's the "digital turn", a term used by Carpo (2013) to describe the changes in architecture design brought by the computer possibilities.

This opportunity was not overlooked by researchers interested in stereotomy and in Italy first Trevisan (1996) [2] and later Fallacara (2003) made the first approaches to stereotomy using digital tools instead of the classic methods. Following many other experiments, the current development of stereotomy cannot be described without acknowledging its resurgence due to the possibilities offered by digital tools. Computational design is therefore an unavoidable defining factor in today's explorations of stereotomy, among other agents which contribute to the development of a stereotomic project.

2. EXPANDING STEREOTOMY BY REVISING ITS SEMANTICS

While classic stereotomy is easily definable within closed concepts such as stone, chisel or descriptive geometry, the current range of experiments make it more difficult to enumerate what are the defining concepts of this art. This apparent distance between current stereotomic practice and the framework present in the treatises creates a void in the theoretical support which once was the backbone of the stone cutting discipline. A critical look into two systems of stereotomy analysis present in a classic treaty (Frézier 1738) and in a contemporary thesis (Fallacara 2003), shall be surveyed under current constraints and possibilities. This analysis provides information for the generation of a classification for further understanding contemporary based in three main categories: *Tomotechny*, *Equilibrium* and *Voussoirs*.

Tomotechny

The Tomotechny category includes all the concepts tightly related to sectioning, be it physically or geometrically. The processing of stone to create the necessary voussoirs, once relying in manual handling of the mallet and chisel, is now dependent on machinery controlled by computers, narrowing the distance between the designer and the worker. In another level, within Classic Stereotomy, the technical drawing method remained two-dimensional, while today it is possible to design a whole structure within a virtual three-dimensional virtual environment.

Equilibrium

The Equilibrium category deals with all the design factors which contribute to the statics success of the structure. The statics calculation, found in Fallacara's (2003) triad is also present in Frezier's (1738) treaty, although it accounts to less than five per cent of the content, showing how intuitive and rule of thumb based was this subject during classic stereotomy. Today, its engineering knowledge is far greater, and it influences directly various design options through digital tools like RhinoVault which

Figure 1
Faceted classification organized in a indented list.

A	**TOMOTECHNY**
AA	**MATERIALIZATION PROCESSES**
AAA	Subtractive
AAAA	- 2D cut
AAAAA	- Milling
AAAAB	- Laser / Blade
AAAB	- 3D cut
AAABA	- Milling
AAABB	- Saw
AAABC	- Wirecutter
AAABD	- Water jet
AAAC	- 3D carve
AAACA	- Chisel and Mallet
AAACB	- Milling
AAACC	- Saw
AAB	Additive
AABA	- Material Extrusion
AABB	- Binder Jetting
AAC	Formative
AACA	- One-off Mould
AACB	- Reconfigurable Mould
AB	**CENTERING**
ABA	Temporary
ABAA	- Support structure below
ABAAA	- Extruded grid
ABAAB	- Per-Voussoir
ABAAC	- Along lines
ABAB	- Tensioned voussoirs above
ABB	Permanent
ABBA	- Composite
ABC	Inexistent
ABCA	- Self supported
ABCB	- Externally supported
AC	**TECHNICAL DRAWING METHOD**
ACA	2D
ACAA	- Trait
ACAB	- Descriptive geometry
ACB	3D
ACBA	- Computerized model
ACBB	- Computational model

B	**EQUILIBRIUM**
BA	**MACRO-SHAPE**
BAA	**Generation method**
BAAA	- Top down
BAAAA	- Constant Profile
BAAAB	- Varying Profile
BAAB	- Bottom up
BAABA	- Hanging model
BAABB	- Graphic statics
BAB	**Continuity**
BABA	- Segmented
BABB	- Continuous
BB	**STRUCTURAL FUNCTIONING**
BBA	Compression only
BBB	Compression and tension
BBBA	- Tension resistant voussoirs
BBBB	- External reinforcement
BBC	Tension only
BC	**SURFACE SUBDIVISION**
BCA	One level subdivision
BCAA	- Pattern
BCAAA	- Periodic
BCAAB	- Non-periodic
BCAB	- Performative subdivision
BCABA	- Curvature
BCABB	- Aesthetics
BCABC	- Voussoir dimensions
BCB	Multiple level subdivision
BCBA	- Courses and voussoirs
BCBB	- Micro voussoirs within macro
BD	**FOUNDATION**
BDA	**Site fixation**
BDAA	- Pre-existing static base
BDAB	- Purposed static base
BDAC	- Tensioned springers
BDAD	- Wall or lintel supports
BDB	**Springer**
BDBA	**- Materiality**
BDBAA	- Same as voussoir
BDBAB	- Different material
BDBB	**- Geometry**
BDBBA	- Subdivision coniтuinty
BDBBB	- Specific design

C	**VOUSSOIRS**
CA	**MATERIAL**
CAA	**Sustainability**
CAAA	- Extraction
CAAB	- Transportation
CAAC	- Processing
CAAD	- Fabrication
CAB	**Structural performance**
CABA	- Compression
CABB	- Tension
CABC	- Weight
CAC	**Material typology**
CACA	- Subtractable materials
CACB	- Formable materials
CACC	- Addable materials
CB	**INTRADOS AND EXTRADOS**
CBA	**Surface**
CBAA	- Double Curvature
CBAB	- Single Curvature
CBAC	- Planar
CBAD	- Textured
CBB	**Perimeter**
CBBA	**- Concavity**
CBBAA	- Convex
CBBAB	- Concave
CBBB	**- Correspondence**
CBBBA	- Analogous
CBBBB	- Differentiated
CC	**CONTACT SURFACE**
CCA	**Geometry**
CCAA	- Ruled
CCAB	- Planar
CCAC	- Composite
CCB	**Friction**
CCBA	- Smooth
CCBB	- Rough
CCC	Mortar
CCCA	- Gap filling
CCCB	- Binding
CCD	Interlock
CCDA	- Alignment
CCDB	- Sliding prevention
CCDC	- Cantilevering

implement graphic statics, or Kangaroo which uses the theory of hanging chains. The subdivision of a surface, essential to the correct load transfer between parts, is also a focus of research today, using computer iterative processes to achieve optimal solutions.

Voussoirs

The Voussoirs category accounts for the design possibilities within the stereotomic structure constituent blocks themselves. Most of the signifiers within this category, such as geometry of the contact surface, or structural performance of the material, find direct homologues in classic stereotomy. However, even in such a timeless concept such as constructive block, the computer has given contributions to their development, such as using different materials thanks to digitally controlled deposition in additive processes, or bespoke contact surfaces with accurate CNC control of fitting features.

Using these three categories and its terms as starting points, it is clear how a direct relationship to classic stereotomy may be formalised. In the attached image, a more developed classification based in the three main semantics is presented, hinting at the variety and richness of its sub concepts. The classification is hierarchical, providing for a logic location of stereotomy related concepts. Each of the three main categories is assigned the initial letters A, B and C. All the main terms inside each of these initial categories is assigned sequential letters, resulting in "AA, AB, AC, etc.", and further into "AAA, AAB, etc."

3. APPLICATION - CASE STUDIES

In this section, two case studies of stereotomic design will be subject to an analysis under this semantic classification. Besides unveiling changes and permanences from classic to current stereotomy, this classification allows for an identification of processes and properties of stereotomic design, effectively allowing for a clearer definition of stereotomy today.

3.1 Arles City Hall

General description. The Arles City Hall entrance vestibule vault is repeatedly referenced within the context of French high stereotomy for its sensitive integration within the whole project and bold ratio of span to rise. This project, ultimately realised by Jules Hardouin-Mansart in 1676, has a convoluted history. Initially planned by La Valfenière, the project was discarded and eventually demolished because a neighbouring house was acquired by the council, in order to enlarge the overall footprint. While the new project was taking shape, Mansart visited the city and was invited to comment on the project. This resulted in numerous modification proposals, most notably in the large hall in the ground floor.

Regarding this hall, consisting of a large vestibule with four central columns, Mansart is said to have expressed "qu'il avoit quelque chose de mieux à faire" (Etlin 2009). This feeling resulted in the project of the low vault with no middle support which we can see today. This vault was finalised by Jacques Peytret, a local architect (and also documented as a painter and painter-architect), who was given plans by Mansart so that he could have the stones cut in the relevant way to achieve Mansart's vision. However, this vision was not totally realised, as Peytret was found to raise the vault without Mansart's consent. It is also suggested by Etlin (2009) that the double vaulted corners were changed from original trompes. Notwithstanding these changes, the built vault is impressive for with swift movements connecting the columns which bring the weight to the ground, even if only figuratively. Together with its proportions of 16 meter width to a shallow 2.43 meter rise, a remarkable feature of this vault is its naked aesthetics Pérouse de Montclos (1982), which is much closer to a contemporary expression of architecture than the profusely decorated vaults of Spanish or Italian tradition. The surface of the center part of the vault looks as one continuous flowing surface, similar to concrete shells of the mid-20th century, instead of overly euclidian arches and domes of a previous renaissance period.

Semantic analysys. Following, a systematic analysis of the Arles city hall vault will be taken according to the semantic structure exposed in the previous section.

Figure 2
Side perspective from the interior of the hall showing its composite surface flow towards the columns which compose the space. [3]

Figure 3
Bottom up perspective of the Arles vault, showing the vault in almost its entirety. 3D projection created by the author from full range panoramic view provided by [4].

Starting with the same structure of the previous chapter, the vault will be analysed starting from the Tomotechny (A) category. Most certainly the materialisation process (AA) for the production of the voussoirs in the Arles vault was achieved by carving (AAAC) stone with instruments related to the chisel, a manual and mostly sculptural way of subtracting (AAA) material from stone (CACA). Although this is probably true for most of the voussoirs, Tamborero (2003) suggests that the first rows which make the connection to the perimeter wall are corbelled and thus should have been square cut. This hint to the possibility of the usage of a saw (AAABB) for achieving planar cuts.

Regarding the first level of classification within centering (AB), its ephemerality, which could range between Temporary, Inexistent or Permanent, is clearly a Temporary Centering (ABA) in this case. Most likely built in wood truss-like support structures below (ABAA) which stones would be laid on, the literature finds evidence of a staged construction in which a main arch is first erected. This shows evidence of elected guide lines along which the vaulted construction would depart from, of which Tamborero (2003) is assertive to suggest its specific order: the periphery arches and the twin lunettes, the large arch, the small vault with the large entrance lunette and finally the large vault.

The drawing method used by Mansart to designate the vaults' surfaces and, consequentially, the voussoir shapes is based on the trait, a series of geometrical operations which would forerun descriptive geometry. This is more over stressed by the words found in the archives (Boyer 1969) such as "(Mansart) baillera le trait a celui qui le conduira", or "les instructions modèles et panneaux pour lesdits bâtiment et voûtes", which clearly reference the traditional drawing methods used in stereotomy prior to Monge's innovation. Although the drawing seen in is not by Mansart or Peytret's hand, it is illustrative how the drawing method within this project is limited to the two dimensional realm and, although the final solution is three-dimensional, the prerogatives always depart from planar compositions which are then projected along straight or circular directrixes.

In the chapter of Equilibrium (B), the first signifier analysed is that of macro-shape (BA), further subdivided in generation method (BAA) and continuity (BAB). The vault was designed with top-down (BAAA) strategies, using established curves (such as the circular arc, or the five center basket-handle arch - anse de panier). These curves are used as generatrices isometrically translated in space, thus exhibiting a constant profile (BAAAB). There is one exception regarding isometry, the central lunettes seen in red in, whose generatrix grows in order to create a interception line which promoted the reading of the V shape which seems to separate the large vault from the small vault. The continuity of the total vault surface is clearly segmented (BABA) with 17 independent surfaces which connect with each other in ridge edges.

The structural functioning (BB) of this vault is based in compression resistance (BBA); this signifier is connected to the material (CA) which will be discussed below. This kind of structural behaviour is only efficient in certain conditions, one of which is the direction of the contact surfaces (CC), whose geometry is directly dependent on the surface subdivision (BC) design. Within this signifier, it is possible to identify a clear separation of courses (rows) of stone (BCBA), predominantly running in horizontal paths. The design strategy could be that of dividing the profile curve of each surface in segments which translate into the parallel courses constant width; these courses are then subdivided in voussoirs of varying length, prioritising available stones blocks sizes. This surface subdivision in two different steps fits within the multiple level subdivision (BCB) signifier.

Another semantic within the equilibrium group is the foundation (BD), which describes the strategies used in the contact between the vault and the rest of the architecture structure. The vertical continuity of the vault surface seems to transfer the load to the columns which surround the space, providing the whole ensemble with a subtle lightness which lift the weight of the large stone ceiling. However, the columns are hardly the sole supports of the vaults, being the thick stone walls (BDAD) behind these which support the vaulted stone structure. The springer (BDB) voussoirs, although corbelled and exhibiting square angles in their extrados, have they geometry (intrados subdivision design) in continuity (BDBBA) with the rest of the structure.

The final semantic group to be discussed is that of Voussoirs (C). Within the material signifier (CA), sustainability (CAA) is analysed with standards contemporary with the vault construction. Being a pre-industrial era, the extraction (CAAA) and processing (CAAC) of raw material was not characterised by significative embodied energy, giving hints to the suitability of the construction method at the time. As expressed while analysing BB, the stone structural performance (CAB) is mainly due to its compression resistance (CABA) and significant weight (CABC). Stone itself fall into the subtractable materials (CACA) typology (CAC) for its volumetric nature upon availability, ready to be cut and carved in order to achieve the intended voussoir shape.

Regarding the geometry of the voussoirs, there are two main categories: intrados and extrados (CB), and contact surface (CC). Regarding the first, the surface geometry (CBA) is mainly characterised by its double curvature (CBAA) in the end of the large vault and small vault. The double curvature is easily identifiable by the curved intrados perimeters (rows) in , where single curvature (CBAB) is present in the lunettes, identifiable by the straight lines in the courses. The perimeters (CBB) themselves are also important regarding many materialisation methods; in this case, we may only observe the intrados perimeters, which exhibit convex (CBBAA), as well as concave curves (CBBAB). Although the extrados is not accessible, stereotomic tradition at the time suggests the extrados is analogous (CBBBA) with the intrados, even if of a rougher nature. The contact surface of these voussoirs are mainly ruled (CCAA), although the circular and linear nature of the subdivision produces also planar (CCAB) and mixed, composite contact surfaces (CCAC). The execution of this vault is very accurate, discarding the need for gap filling mortar; however, it is noticeable a thin mark of material between voussoirs, whose purpose should mainly be related to binding (CCCB) blocks together to facilitate the construction process - despite the binding purpose, every mortar is always efficient in gap filling (CCCA), even if in a micro-scale. Friction itself (CCB) is mostly related to the fine texture of the contact surface, which is hidden behind the vault intrados surface. Following the recommendations present in most stereotomy treatises, it is expected that the contact surface is left rough (CCBB) enough to cause large friction between the voussoirs and contribute to the stability of the ensemble.

3.2 Armadillo Vault

General description. The Armadillo Vault is an experimental construction built for the 15th International Architecture Exhibition - La Biennale di Venezia 2016. It's key feature lies in the coverage of a large space with stone elements not binded by any adhesive or hardware, adding to the expressive sinuous forms which result from the performative shape. This work is a super demonstration of the knowledge accumulated within the Block Research Group (BRG),

Figure 4
The Armadillo vault is a stereotomic construction which is developed around the columns of the Corderie dell'Arsenale in Venice. [1]

Figure 5
Top view of the pre-assembly of the Armadillo Vault. Notice that there are no columns puncturing through the structure. (Block, Rippmann, e Mele 2017) Photo credit: ETH Zürich / Anna Maragkoudaki

creating the most complex stereotomic surface to date. This complexity, present in the amount of different voussoirs, free form surface, and extreme accuracy of fabrication and assembly, is counteracted by a seemingly simple and graspable curvilinear form which seeks to resolve a space within the large Venice building.

The vault is designed with the main purpose of showcasing the possibilities of contemporary stereotomic construction and material efficient equilibrium structures supported by TNA (Thrust Network Analysis), the framework developed by Philippe Block (2009) based in graphic statics which allows for a precise modelling of structure in equilibrium, be it compression or tension. The application of this design method to stereotomic constraints such as subdivision and voussoir materialization is largely developed by Matthias Rippmann (2016) in hid PhD thesis.

This structure was built by the Escobedo Group, a texan masonry company which works closely with Block since at least 2009. This relationship continued with the research on the MLK Jr. Park Vault, a bold stereotomic structure which, although provided much of the pretext for Rippmann's research, still did not come to realisation. As such, the Armadillo may be understood as a sort of proof of concept for this kind of construction approach in the contemporary context, having fully proved its validity.

Contemporary freeform stereotomic construction with stone is not a first, as can be seen in the works of Fallacara or Yoon and Höweler. What is impressive about this vault are the numbers, which in the end allow for the integrated complexity of the whole. The vault is composed of 399 bespoke stone voussoirs weighing a total of 23.7 tons, whose thickness range from 5 to 12cm. These thicknesses are impressive knowing that the largest spans exceed 15m, making the thickness to curvature radius comparable to that of an egg-shell. These extreme in material economy is justified by the team by "the prescribed weight limitations on the floor of the exhibition space in the protected building", but also important for reducing building embodied carbon and energy, together with making construction costs competitive: this can only be achieved for the compressive only nature of the construction systems, highly optimised with the TNA approach.

Semantic analysys. The Armadillo vault, being an exceptional work of stereotomy in the contemporary era of this discipline, is a very adequate example to analyse under the semantic classification.

In order to understand the shape of the Armadillo vault, the Equilibrium (B) category provides the key signifiers for this task. The macro-shape (BA) is obtained with RhinoVault, a plugin developed for the 3D computational modeller (ACBB), which is an application of TNA, based in graphic statics (BAABB). Signifiers starting with BAAB indicate that the generation method was bottom up, explaining the seemingly free form shape of the vault. This shape is continuous (BABB), meaning there are no tangential breaks, which would hint to multiple single surfaces sharing edges. One of the reasons for such a non-euclidian shape is the design team's purpose of reducing the shell thickness to its minimum, within the 5 to 12cm range. This means that there must be no location in the intrados or extrados set more than 6cm further than the thrust surface, much as an arch must contain its thrust line within its volume. Being the thrust surface a complex network derived from catenoids, using circle arcs would force the thickness to values deemed too large for the thin design intent.

This construction is composed of stone blocks pressed together in a dry joint, without resorting to any kind of adhesive or mechanical fixations. This is only possible due to compression only (BBA) structural functioning (BB) of this structure, which is dependent on the correct orientation of the contact faces. This orientation is given mainly by the surface subdivision (BC), which ensures that the contact surfaces (CC) of the voussoirs (C) are as perpendicular as possible to the thrust vectors. In this case, a multiple level subdivision (BCB) was chosen, mos specifically a division in courses and voussoirs (BCBA).

The foundation (BD) characteristics of this project are very particular due to the constraints related to protecting the historic flooring of the Corderie. As such, instead of inserting foundation piles, the usual outwards thrust of the springers was retained with tensioned (BDAC) cable ties between themselves. These springers are large crafted steel elements (BDBAB), whose unique geometry (BDBBB) is capable of absorbing up to 11 voussoirs.

The solutions adopted in the voussoirs (C) are key to the success of this construction. Their material (CA) is stone, a subtractable material (CACA) materialised by two 3D cut (AAAB) processes: circular saw cutting (AAABB) for the intrados rough cuts and approximation cuts for the contact faces, and milling (AAABA) with specially crafted bits for the contact faces finishing. Stone has low embodied carbon and energy mainly in its processing (CAAC) which is nearly negligible, and plays excellent structural performance (CAB) in what comes to weight (CABC) and compression strength (CABA). While the extrados surface (CBA) is planar (CBAC), the rough cuts in the intrados provide a textured finish (CBAD), one of the aesthetic signatures of this work. Contact surfaces (CC) are ruled surfaces (CCA) which feature a registry notch mainly for alignment purposes (CCDA).

Within Tomotechny (A), the signifiers technical drawing method (AC) and materialisation processes (AA) were already discussed above. Regarding centering (AB), the Armadillo vault was erected thanks to multiple temporary (ABA) extruded grids (ABAAA). These curved wooden lattices were supported on standard scaffolding, and the voussoirs were laid on top of shims which allowed for more flexibility while assembling.

3.3 Comparison between classic and contemporary stereotomy

One of the possibilities offered by a semantic classification framework, besides the already intrinsic analysis of a stereotomic work, is the structured comparison of two different works, even if separated by 340 years. As such, the semantic classification will be used to understand changes and permanences from the Arles vestibule to the Armadillo vault. The graphic in allows the immediate grasping of differences and similitudes between the two analysis. Most of the graphic is purple, revealing the common characteristics which understandably include the broader terms, such as Voussoirs, or Materialization Processes. As the branching goes farther from the center, differences start to emerge.

Out of these we highlight as differences the tools used for Materialization - AA (chisel and mallet vs CNC sawing and milling), the Technical Drawing Method - AC (trait vs computational model), the Continuity of the vault surface - BAB (segmented vs continuous) and the Generation Method - BAA (top down vs bottom up).

On the other hand, the similitudes are shared between Subtractive Materialization Processes - AAA, similar Centering strategies - AB, same Structural

Figure 6
Summary of the results of semantic analysis of both projects.

	ARLES CITY HALL	ARMADILLO VAULT
TOMOTECHNY	AAAC ABAA ACAA	AAABB/AAABA ABAAA ACBB
EQUILIBRIUM	BAAAB BABA BBA BCBA BDAD BDBBA	BAABB BABB BBA BCBA BDAC BDBAB/BDBBB
VOUSSOIRS	CAAA/CAAC CABA/CABC CACA CBAA/CBAB CBBAA/CBBAB CBBBA CCAA/CCAB CCBB CCCB/CCCA	CAAC CABA/CABC CACA CBAC/CBAD CBBAA CBBBA CCAA CCBB CCDA

Functioning - BB and Surface subdivision in Courses and voussoirs - BCBA. The common usage of stone for the voussoirs is reflected in all the signifiers under Material - CA, whose voussoirs both present Convex - CBBAA and Analogous - CBBBA perimeters of Intrados and Extrados.

These two compared architectural works are set apart by 340 years, an extended time range which feels even larger due to the exponential growth of technology (Kremer 1993). Notwithstanding the expected change of paradigms, the amount of similitudes between the two works is understandably rooted in their common raw material - stone - which predates even human history. The intrinsic properties of this material and its related signifiers are maintained, such as the compression structural performance, or the subtractive fabrication methods. Philibert de l'Orme is quick to exalt the qualities of stone construction, justifying the need for stereotomy as a means to build large spans with limited sized elements such as voussoirs. His arguments are still valid today as can be seen in the structural stability of the Armadillo Vault or the fire resistance of the Notre Dame of Paris vaults under the 2019 roof fire.

By distancing ourselves from stone as the main common denominator of both vaults, the changes are rooted in the possibilities provided by digital technologies. The computer is an essential part of current electronic control of machining tools, actually being responsible for the current possibility to build stereotomically today; the digital design / digital fabrication flow has taken the void place left by the disappearance of the vault designer / stone mason since the introduction of steel in construction. Besides this relevant part taken by the computer in the resurgence of stereotomic design, there is another important role taken by digital technologies which is that of shape. Missing powerful calculation tools led classic designers to resort to known shapes, or derived surfaces from these, accounting for the abundance of circles and "basket handles" composed of up to seven arcs of circle. On the other hand, computational power led to the creation of discrete meshes and Bézier splines which are used by bottom up processes to calculate unimagined shapes which satisfy the requirements of the designer. One of these requirements might be the continuity of a vault, something trivially found in an unified mesh under a common network of forces, but not so immediate as can be seen in the triangular separation of the big and small vaults of Arles.

Figure 7
Intersection of the two semantic analysts above - Arles vestibule in blue, and Armadillo vault in red. The signifiers not present in either work are left in grey, and the common signifiers are painted in purple, hinting at the permanences.

4. CONCLUSION

The surveying of the two case studies above is instrumental in identifying similitudes and contrasts between two stereotomic structures whose design and construction dates are set more than three centuries apart, with Industrial and Digital Revolutions between them. A clear set of permanences are identified, such as stone and the compression only nature of the structure, while differences arise in the generation method of the macro-shape or the tools used to dress the stone. The main differences detected in the analysis of a flow from classic to contemporary stereotomy are directly or indirectly related to technological developments made possible due to the digital possibilities. Stereotomy, being the art of construction with carefully shaped blocks which support each other, gains its built expression from its direct constraints and related meanings. These semantics become the definers of an augmented stereotomy, greatly expanded today with digital technologies. The use of a structured semantic classification of stereotomy is instrumental in reading and supporting this on-going evolution.

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The Roots of 4IR in Architecture

A military drawing machine used for space perception in architecture

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This paper analyses how architecture became a pioneer discipline in digital interactivity research. It describes how that pioneer research derives from a lineage of researchers whose work spans more than two decades beginning in the early fifties. Military funds enabled the creation of the first computer graphic interfaces that evolved into a ``drawing machine'', the first interactive CAD, that made possible the role of architecture as a pioneering discipline in interactivity research. It is expected to demonstrate that the same architecture that nowadays uses mainly interactive digital design was one of first disciplines to research interactivity addressing a gap in the study of the link between architecture and interactivity.

Keywords: *CAD, interactivity research, architectural design, ,*

INTRODUCTION

The issue of digital architecture being of great importance for the change in architectural practice seems to be, simultaneously, a controversial and key issue. However, this article does not intend to discuss such issue, but rather to demonstrate the importance of architecture as a pioneer discipline in the use of interactive digital design.

It is our intention to show that architecture was a pioneer discipline in interactivity research and especially in interactive digital design research. That approach descended from a lineage of researchers that had begun in the early fifties with the first computer graphic interfaces, continued with the first interactive CAD and in the late sixties originated the creation of an architecture research center based on that interactive CAD. We show how a military “drawing machine”, the interactive CAD, enabled architecture as a pioneering discipline in interactivity research.

This article is focused on design research made for the American military industry, that would led to the use of interactive CAD in architecture. We will highlight the links of a research project, created in late fifties for military purposes that would be followed within a decade by important research on interactivity and graphical interfaces. That project of creating a military “drawing machine” was called Project CAD.

Several authors (Rocha, 2004; Llach, 2012, 2015; Steenson, 2014, 2017) considered the study of the origins of the use of computational methods in the field of architecture as a part of the change in the creative process, in the methods of design and even in architectural research, however, as already mentioned, in the present investigation the objectives are different and here is shown how Architecture played a pioneering role in the research of interactivity.

That study of interactive design was not only a pioneering research on interactive digital architecture but also a very important research of interactivity in the sixties. Thus, with this contribution, architecture played an important role in interactivity and in 4IR.

With this research we hope to demonstrate that the same architecture that nowadays uses mainly interactive digital design was one of first disciplines to research interactivity addressing a gap in the study of the link between architecture and interactivity.

METHODOLOGY

The adopted methodology is based on historical research. The criteria for data selection was based on the relevance to digital architecture history and on the links between the research and the scholars involved. The objective was to validate the less recognized direct relationship between interactivity in computer graphics and the use of that interactivity in architectural research.

The bibliographic collection involved primary and secondary sources, doctoral theses, books, periodicals and other publications, articles and scientific communications, bibliographical notes, in analog or digital format, audio and video formats as well as web pages and other documents in electronic format only.

ORIGINS OF THE FIRST INTERACTIVE CAD AT MIT

The beginnings of computer graphics research in the early fifties and the use of interactive CAD in architectural research in the next decade have in common not only the institution, Massachusetts Institute of Technology - MIT but also the military purpose of the research and especially the military industry production.

To understand the relationship between those two beginnings, it is important to understand the question of academic research made for military industries. The design process that was used by the main manufacturers of military, automotive, shipping and aeronautical industries in the fifties needed more complex geometries that could only be possible by using a design supported in computation. Therefore computer-aided design emerged as a solution to create those new geometries in those industries (Weisberg, 2008; Perry, 2014; Llach, 2015).

It is important to mention that, although there were important contributions to the development of CAD from the automotive industry like Bézier and Casteljau (Farin, 2002; Carpo, 2011) and aeronautical industry like William Fetter (Perry, 2014), this article targets MIT's research for the American military industry.

This article focuses on the role played by the MIT's researchers and it seeks to associate the origins of CAD in a Cold War military funded project with the beginning of interactive digital architecture and to demonstrate that a research project that intended to create a "drawing machine" for military purposes contributed to a pioneering use of interactivity in architectural design research.

In the early decades of post-World War II, in the Cold War period, MIT's computer graphics research, was based on financing for military purposes, namely for defense industry and included research in areas that are in the origins of CAD and Computer Aided Manufacturing (CAM). That military funding at MIT had such level that several authors considered the institute to be the largest recipient of public research funds in the first decades of the Cold War (Weisberg, 2008; Perry, 2014; Llach, 2015).

It was a time when computers were very expensive, to the point that the cost of using a machine in the early sixties was almost ten percent of the total cost of a major research project in which three hours of computer use had the same cost as the monthly salary of a junior engineer - six hundred dollars (Weisberg, 2008).

In the aftermath of World War II, the US military started to fund human - machine interaction research to the point that in December 1951, only six years after the end of the War, MIT researcher Jay Forrester introduced Whirlwind, world's first computer with digital display, on a CBS television broadcast. It was a computer connected to a 256-pixel monitor used by the American Navy to simulate the ballistic missile course, its fuel and speed (Forrester and Everett, 1990; Weisberg, 2008; Llach, 2015).

This Whirlwind's interface, the first computer screen, worked like a fifties television set, through a cathode ray tube (Forrester and Everett, 1990; Llach, 2012, 2015; Perry, 2014). By the end of the fifties, Whirlwind, would have a second human interface, the light-pen, developed by Wesley Clark, which allowed data input directly on the screen, initially for military purposes related to radar coordinates (Llach, 2015).

By the end of the decade, and according to Llach (2015), Whirlwind, would allow the development of MIT's first computer-aided drawings. However, those drawings were the offspring of a noninteractive system and despite Whirlwind being an interactive computer, the design was programmed by punched tapes through a programming language, the Automated Programming Tool (APT). APT was created to control a milling machine and had been developed by the same Servomechanisms Laboratory that created Whirlwind, by then called Electronic Systems Laboratory - ESL (Weisberg, 2008; Llach, 2015).

APT was a language designed for manufacturing and in a few decades, it would become widely used in the aeronautics industry. The APT had been developed under the coordination of the electrical engineer Douglas Ross who would become one of the co-directors of Project CAD with Steven Coons, a design professor at the mechanical engineering department (Weisberg, 2008; Llach, 2015).

Project CAD was a joint venture between ESL from the department of electrotechnical engineering and the design division of the mechanical engineering department. In nowadays terms it could be said that was a partnership between IT coders and designers. A research project that had as generic objectives, stated in the military financing contracts, the improvement of the design in the manufacturing of airplanes, missiles and respective components. The project that would last from 1959 to 1970, through three contracts, had has as its real purpose to create a "drawing machine" for the military. (Weisberg, 2008; Llach, 2015).

The denomination adopted for the project was computer-aided design, with a hyphen between computer and aided. This name was a condition of the design division team to emphasize the idea that the design foreseen in the project was a human process in which a user would be assisted by the computer and not the computer automatically replacing the skilled design workforce (Llach, 2015).

That way, CAD became the acronym of the project's name, computer-aided design, which emphasized the idea that drawing was a human process and not an automatized computer drawing (Llach, 2015). Thus it was created the acronym that corresponds to the most well-known designation of the drawing on a computer procedure (Weisberg, 2008; Llach, 2015).

Coons and Ross had almost antagonistic views of computer design. For Coons, the computer would be an assistant or associate of the human designer, while for Ross, computers would be universal tools with the ability to make a fully automated design. On one side was the possibility of being creative using a computer to draw and, on the other side, was the automated machine intelligence to do the drawing (Llach, 2015).

In fact, Coons's vision of human - machine interactivity would prevail mainly due to difficulties of implementing Ross's design automation. Despite having a great deal of merit in choosing interactivity for digital design, Coons isn't recognized for its role as a design theorist in Project CAD but for its role in the development of computational geometries and, above all, for the creation of the Coons Patches, a mathematical technique for describing three-dimensional curved surfaces by the four boundary lines and their intersections (Llach, 2015).

Steven Coons's work in Project CAD can be considered the origin of how architectural design is mainly done today with a man interactively drawing on a computer (Llach, 2015). Project CAD can also be considered the first systematic investigation of human - machine interaction, before Douglas Engelbart have prototyped the computer mouse at Stanford (Licklider, 1969; Llach, 2015).

Eight years after Whirlwind graphical interface had been created and shown on television, the same research facility was evolving to develop a "drawing machine".

THE FIRST INTERACTIVE CAD - SKETCHPAD

Nevertheless, Coons was not a computer scientist and his ideas of interactive CAD would be materialized by a young electrical engineer and military in reserve, called Ivan Sutherland.

As a teenager, Sutherland was already a computer enthusiast, he and his older brother, Bert, were some of the earliest microcomputer programmers ever, as they were able to program the division into the Simon, a proto-personal computer created by Edmund Berkeley, an acquaintance of Sutherland that presented him to his future advisor, Claude Shannon, an MIT's Ph.D. who, in 1948, had signed a groundbreaking and fundamental article for the digitally connected world of today, "A Mathematical Theory of Communication" (Sutherland, 1989, 1994)

Despite the notorious influence of Coons's ideas, Sutherland, had another motivation for the original idea of his Ph.D. Dissertation, the creation of an interactive CAD software. This other motivation was due to the fact that his father was a civil engineer, and, for this reason, he was able from a young age to read engineering blueprints from his father's work (Sutherland, 1989, 1994).

Sutherland would begin its activity at MIT, in 1960, in the Lincoln Laboratory, MIT's military research facility, using the then-powerful TX-2, a computer with interactivity guaranteed by the light-pen and through a seven-inch screen, complemented by a set of switches and rotating knobs that ensured the manipulation of the drawings, as well as the area and the image size. These mechanisms that manipulated the drawing in the screen, are of some importance for the understanding of the evolution of the digital drawing, since part of what we know today, as tools of digital design manipulation, correspond to Sutherland's inventions, patented in his name, years later, as are the cases of windowing, zooming and clipping (Kassem, 2014).

The interactivity of Sutherland's Sketchpad was inspired not only by Coons's ideas but also by the ideas of JCR Licklider's article "Man-Computer Symbiosis" (1960). Licklider was also an MIT researcher that would became the director of the important Information Processing Techniques Office (IPTO) from the Advanced Research Projects Agency (ARPA). In 1964, Licklider would have Sutherland chosen as is successor as IPTO's director (Sutherland, 1989). Sutherland would consider, years later, that the money spent on research by IPTO would have generated a return to the United States through the tax revenues of businesses and the jobs created. IPTO was also the place were ARPANET, the precursor of the internet, started (Roberts, 1978; Sutherland, 1994).

Even before the delivery of the Ph.D. dissertation, MIT would rush to disclose Sketchpad, still in a provisional version, during the spring of 1962, through the production of a film in which Sutherland drew on that version, since the thesis would only be delivered on 7 January 1963 (Sutherland, 1963, 1994). The film would be widely used in presentations for students, academics and journalists, making it a unique influence for all types of design students, architecture students included (Llach, 2012, 2015; Perry, 2014).

In that January, the first interactive CAD was converted into in a Ph.D. dissertation called Sketchpad, a Man-Machine Graphical Communication System. Coons was on the thesis committee with the Artificial Intelligence pioneer Marvin Minsky (Sutherland, 1963). Sutherland had created an interactive design system on the computer, the first interactive CAD made with a seven-inch screen, almost the size of a smartphone (Kassem, 2014).

Because Sutherland envisage Sketchpad without the need of using punched cards or tapes to transmit commands to make the computer draw, it was a design system that could draw in real-time. The real-time fact which at present appears to have been taken for granted provided the system in 1963 an interactive feature. The system was innovative and introduced new concepts in several areas of computer graphics, such as dynamic graphics, visual simulation, graphic resolution constraints (Negroponte, 1995). "Sketchpad was the big bang of computer graphics"(Negroponte, 1995, p. 103).

The following decades would demonstrate that Sketchpad was a fundamental element for media development, a central part in the history of computational media (Wardrip-Fruin and Montfort, 2003) and a genuine graphic communication system (Manovich, 2013). In fact, Sutherland itself, in the title of his Ph.D. dissertation, identified Sketchpad as a system of graphic communication between man and the intelligent machine and not as a design system.

However, Sketchpad was also more than an interactive communication system, since it can also be considered as the beginning of today's computer animation. Sketchpad was also a pioneer in the field of programming languages, being the precursor of object-oriented programming, since it was the first computer program to instantiate inherited instances and properties between instances. According to Alan Kay, which is considered the "father of personal computer" (Negroponte, 1995, p. 134) and was a Sutherland's student, Sketchpad would have been the first object-oriented programming language ever since it did not use a list of programming procedures (Kay, 1996; Manovich, 2007; Gaboury, 2014).

Only eleven years after Whirlwind had been shown on American national television, that first graphical interface research made possible that a man could use the screen to draw in real time.

STEVEN COONS - CAD IN ARCHITECTURE

Steven Coons can be considered as the main mentor of Project CAD, idealizing a CAD to serve creative designers (Coons e Mann, 1960) like architects. A CAD for designers who started their design on the computer without having a definitive idea, unlike the engineering designers. For Coons, the computer stayed with the repetitive work and the man had the creative work. Coons envisioned the computer as a universal design machine, the "perfect slave" (Coons, 1966, p. 9) serving the man that could be a creative designer or not (Coons, 1966; Kassem, 2014; Llach, 2015)

Although CAD "paternity" appears to be the subject of doubts, recent historiographical investigations of CAD origins, such as Cardoso Llach (Llach, 2015), seem to show that it is safe to say that Steven Coons can be considered the "father of CAD" or at least the person responsible for the designation and the concept of computer-aided design. If on one hand, Douglas Ross who died in 2007, almost thirty years after Coons that died in 1979, claimed during that period that he was the responsible for the Project CAD ideas , on the other hand, the youngest members of Project CAD as Timothy Johnson have ensured, already in this decade that the merit of the Project CAD ideas pertained to Coons (Llach, 2015)

Just as Sutherland who invented the first interactive CAD, Coons is not one of the most well-known figures in architectural design. However, Coons can be considered, without a doubt, as one of the most influential characters in the development of its digital component, with important contributions to the introduction of an interactive technology culture in design. The importance of Coons for design, only began to be recognized in recent academic works like those of Cardoso Llach (2015, p. 54), that considers that Coons had a "key role as a design technologist and theorist" or Gaboury (2014, p. 143) that calls him the "grandfather of the computer graphics".

When Sutherland, after delivering his Ph.D., returned to the US Army, Coons became the main promoter of Sketchpad. The system's first presentation to an architect's audience was done by Coons at the "Architecture and the Computer" conference in 1964, reinforcing the importance of the symbiosis between architect and computer (Rocha, 2004; Kassem, 2014; Steenson, 2014).

Without Sutherland, Coons would continue research on the development of the "drawing machine" with Timothy Johnson, developing a three-dimensional version of Sketchpad, taking advantage of internet pioneer Larry Roberts's Ph.D. dissertation on computer representation of polygons (Roberts, 1963, 1978; Coons, 1967).

The three-dimensional version of Johnson, Sketchpad III, delivered as a master's thesis, five months after Sutherland's Ph.D., is nowadays possibly better known than the original version due to the 1965 documentary, broadcasted in National Educational Television (NET). In this movie, the Johnson is drawing in the screen with an introduction made by Coons in an interview (Johnson, 1963; Morash, 1965).

Sketchpad III was the first computer graphic system to implement three orthogonal views of 3D objects at different scales. The goal of Johnson and Coons was to enable prospective design if necessary. This way the user only needed to rotate the object with the computer's rotary knobs. With Sketchpad III the viewport concept was established continuing to be present in CAD software up to the present times (Weisberg, 2008; Llach, 2015)

Coons emphasized the importance of the symbiosis between creative designers and computer reinforcing the idea that the computer is only an aid to man "the perfect slave". An idea created by of Coons in a presentation that he made at a regional congress for arts teachers in 1966 to demonstrate the utility of the machine in artistic creation (Coons, 1966).

A few months later, Coons would have the chance to take interactive design to architecture by being one of Nicholas Negroponte's master thesis advisors in the architectural thesis The Computer Simulation Of Perception During Motion In The Urban Environment (1966). Negroponte was already beginning to realize the need for scientific research in architectural design (Negroponte, 1966, 2010). A vision that corroborate the ideas of the contemporary Design Methods movement and of Horst Rittel that considered the hypothesis of bringing NASA approaches to design science (Bayazit, 2004).

Already in the present decade, in an interview, Negroponte would highlight the importance of its three advisors, and in particular, Coons, due to its relevance to the evolution level of digital architectural design (Negroponte, 2010; Llach, 2012, 2015). The other two advisors were Kevin Lynch, specialist in urban planning, author of the important book The Image of the City and Gyorgy Kepes, a visual artist who had taught in the New Bauhaus de Chicago with Moholy-Nagy (Negroponte, 2010; Steenson, 2014).

However, the influence of Coons as Negroponte's advisor is far more important for the evolution of the interactive CAD, even by the fact that it has originated the start of Negroponte's teaching and researching activity at MIT. In fact, the architect would become professor of an MIT's engineering course due to Coons. Negroponte, in 1966, replaced Coons who had taken a sabbatical leave, to be able to work again with Sutherland, now at Harvard (Llach and Forrest, 2017). Negroponte was a computer-aided design assistant professor in the mechanical engineering course while Coons with Sutherland were working on a Virtual Reality pioneering research that would be published as "A head-mounted three-dimensional display" but would be better known as Democles Sword (Negroponte, 2010; Llach and Forrest, 2017; Steenson, 2017).

Negroponte would move from the mechanical engineering department to the architecture and planning school the following year. There he could create one of the first computer-based architecture research centers, the Architecture Machine Group (AMG) (Rocha, 2004; Negroponte, 2010; Steenson, 2014).

In just three years, after the departure of Sutherland, Coons would achieve important developments in the" drawing machine", helping to create the three-dimensional version of Sketchpad, disseminating interactive CAD to architects and visual artists and managing to find an architect to continue the development of Interactive CAD research in architecture.

NEGROPONTE AND AMG

In 1968, Negroponte received an invitation from the Dean of the MIT's School of architecture and planning, to become an assistant professor in the architecture department, creating one of the first computer-based architecture research centers, the AMG (Rocha, 2004; Negroponte, 2010; Steenson, 2014).

During the late 1960s and early 1970s, Negroponte, through the AMG, engages in several research projects, URBAN 2, URBAN 5, SEEK, or HUNCH, which linked interactive computing to space perception in architecture. Projects that used interactive design to improve the perception of the designed space, funded mainly through military funds (Steenson, 2014).

The initial projects, URBAN2 and URBAN5, used a simple graphical interactive CAD, combined with a robotic arm to move three meter cubes that came from an artificial intelligence research domain called Block Worlds (Steenson, 2017). The research enabled an interactive communication between man and computer. A communication established through the computer keyboard and buttons by question and answer (Negroponte, 1970; Steenson, 2017).

AMG's next project, an evolution of URBAN5 but in which the arm reconfigured the blocks according to the habits of the inhabitants. A research that tried to emulate a city with an environment reconfigurable by the inhabitants, a colony of gerbils (Negroponte, 1970, 1975; Steenson, 2014, 2017).

The inhabitants of the SEEK "city", the gerbils, were chosen for their curiosity and served to introduce the "chaos" element into the simulation of the real world. SEEK aimed to show the reflexes of a responsive environment, with a robotic arm correcting or amplifying the changes caused by gerbils (Negroponte, 1970, 1975; Steenson, 2014, 2017; Llach, 2015)

The technology that was included in the SEEK software was tied to other MIT artificial intelligence laboratory researches, related to computer vision and the ability to analyze incompatible data. The MIT's artificial intelligence laboratory, at the time, worked in researching the construction of a practical system of analysis of real-world scenarios and Negroponte developed investigation with the laboratory through its researcher, Marvin Minsky, the Artificial Intelligence pioneer who was with Coons on Sutherland's Sketchpad thesis committee (Negroponte, 1970, 1975; Steenson, 2014, 2017; Llach, 2015).

Another important project of the AMG related to interactive CAD was HUNCH, directed by Negroponte with research done by James Taggart in his Master Thesis (Taggart, 1973).It was a project more closely related to Sketchpad and also to architectural digital design (Negroponte, 1975). It consisted on a system that deciphered early versions of hand sketches to the computer screen using artificial intelligence combined with cybernetics, architecture, behavioral cognition, construction and machine learning (Werner, 2018). In HUNCH, the sketches made by the human hand were considered a vehicle for computer learning, following the concept that much of the thinking involved in architectural design was made in the form of sketches drawn in napkins and scraps of paper. It was more than a drawing system through sketches, since it could also interpret the pressure and density of the lines drawn by the user and could also perform the rationalization of the drawing through B-spline techniques, a research area developed in that initial period of the seventies by Coons and his disciples (Negroponte, 1975; Werner, 2018).

The importance of Negroponte projects to the interactivity research would make JCR Licklider, the author of "Man-Computer Symbiosis" would consider it one of the few researchers to contribute to the advancement of interactivity research in the sixties with a research extent only comparable to Engelbart who invented the computer mouse (Licklider, 1969, p. 619). Licklider with "Man-Computer Symbiosis" (1960) had become one the most important theorists on the interaction between men and electronic computers.

AMG's research projects would provide Negroponte, material for the writing of two important books for digital architectural design, The Architecture Machine (1970) e Soft Architecture Machines (1975). The latter would have a chapter called "Computer Graphics" with introduction by Steven Coons. However, more important than the authorship of the introduction, it may be the fact that Negroponte in that chapter considered his former supervisor as the "father of computer graphics"(Negroponte, 1975, p. 57) . The former advisee also pointed out that he attributed this distinction to the advisor because he considered that there was a great disproportion between the initial objectives proposed by Coons for the interactive computer graphics research and the objectives proposed by his research colleagues at the beginning of the sixties. Almost forty years after the publication of the book, Negroponte continued to emphasize the same idea of importance of its advisor Coons, considering him as the inventor of many of the CAD systems of the sixties (Negroponte, 2010).

In Soft Architecture Machines (1975), Negroponte would also recognize the little progress in computer graphics interactivity, based on the fact that computer graphics researchers were more focused on technical developments in image realism or in data efficiency. Negroponte (1975) even gave as an example of little progress in interactivity, the book Principles Of Interactive Computer Graphics coauthored by one of Sutherland's top students, Robert F. Sproull (Sutherland, 1994).

This marks the distinction between Negroponte's disciples and Sutherland's disciples. Being two of the most important computer graphics research groups of the seventies, they focused on different areas of computer graphics, the first working on interactivity research, the second researching splines, texture mapping and 3D animations. In Sutherland's group were important names that would become university researchers or prominent entrepreneurs in computer graphics, such as Henry Fuchs, Henri Gouraud, Bui Tuong Phong, James Henry Clark, James F. Blinn, Frank Crow, Brian A. Barsky, John Warnock, Frederic Parke, Tom Lyche, Alan Kay, Elaine Cohen, Richard Riesenfeld e Edwin Catmull (Carlson, 2008; Gaboury, 2013, 2015. Of these, the last two were also Steven Coons advisees and Catmull, in his Ph.D. Dissertation was responsible, in 1972, for the first 3D computer-animated film A Computer Animated Hand and after that would create Pixar and become president of Walt Disney Animation Studios.

Negroponte and his disciples were researching another area of computer graphics crossing interactivity with space perception. Authors who researched Negroponte such as Steenson (2014), emphasize that its influence is of a greatness that surpasses the architectural design and extends through systems architecture. Steenson in her doctoral thesis (2014) considers that Negroponte and AMG modeled design as a process of information search giving an important contribution to the notion of information architecture, associating architectural research with cybernetics, self-reflexivity and artificial intelligence approaches. In fact, already in The Architecture Machine, (1970) Negroponte, had a broad concept of architecture and argued that the work with audio, visual and other sensorial qualities was an architectonic undertaking, due to the reach of the architecture and the possibilities of creation of perceptual spaces, thus conceiving the idea of interfaces for architecture machines.

But if the Sutherland's disciples research was important for simple everyday things like digital animation, the work of the disciples of Negroponte was also very important for nowadays levels of interaction with computers. Research that comprised projects like Aspen Movie Map (Bender, 1980; Mohl, 1981; Negroponte, 1995) predecessor of the street view applications or the interactive media room Spatial Data Management System (SDMS) (Donelson, 1977, 1978) but especially by the development of the interaction that had been started with HUNCH with the ability of the computer to interpret the pressure and density of the lines drawn with pioneering touchscreens research, of, predecessors of tablets and smartphones, in a project called "One-Point Touch Input of Vector Information for Computer Display" (Herot e Weinzapfel, 1978). Such projects, also backed by military funds, can today, with no great margin of error, be regarded as appearing to be two or three decades ahead of their time. But more important than being projects of Sutherland's disciples or of Negroponte's disciples, those were projects that descended from Coons and from the ideas that he conceptualized for the military "drawing machine".

Less than 10 years after Sketchpad, the "drawing machine" was turned into a sketch-recognition research at an architectural research center. Five years later it was the turn of finger-drawing on the computer screen, research that preceded the touchscreens, and nowadays smartphones and tablets.

However, it would be decades before the use of interactive CAD in architecture in schools and project offices could be generalized, as can be demonstrated in Mitchell (1977) or Cross (2001).

DISCUSSION AND RESULTS

The article establishes a series of connections between the conceptualization and development of the first interactive CAD and the use of interactivity in architectural research that in previous studies had not been fully articulated. It is revealed a link between the conceptualization of real-time drawing on the computer screen and the ability of using digital interaction in architectural research. Through the academic relationship between Steven Coons, Ivan Sutherland, and Nicholas Negroponte, it is shown a new insight into the early days when interactive digital architecture was launched.

The relationship between three scholars, Coons, Sutherland and Negroponte demonstrate a progression of the interactive design ideas, in the sixties, after a period, in the fifties, when the first computer with graphic display was created and then equipped with a data input, the light pen. First, Coons conceptualized the use of that screen and light pen to enable the interaction between man and machine, through drawing. Then Sutherland, had the ability to create a design software that materialized the ideas of Coons that although not being his adviser, he was a member of the Sutherland's thesis committee. The last of those scholars, Negroponte materialized Coons idea of extending interactive CAD to creative designers. Negroponte would use interactive CAD and interactivity in architectural research to create AMG, a pioneering research center devoted to the use of computing in architecture and to the study interactivity in architectural environments.

It can be concluded that Coons conceptualized a graphical computation with an interactive design, long before all the others that researched in the area. Sutherland had the capacity to materialize the design interactivity envisioned by Coons, creating the first interactive CAD, initially for engineering design. However, Coons considered that an interactive computer could be also a partner of creative designers. This way, he managed to take Project CAD's ideas from the exclusive domain of engineering to architecture, through the work he did as a mentor to Negroponte, bringing interactivity to architectural design. Later, Negroponte took the research of interactivity in architecture to create environments with greater capacity of perception and interaction with the user, outside the strict scope of architecture.

It is shown a link between Coons's original interactive design ideas at MIT's Project CAD and the pioneer work of Negroponte that made architecture one of the firsts disciplines to made research in interactivity. Negroponte, professor and researcher in the department of architecture, adopted the theoretical ideas of his advisor Coons in the study of space perception in architecture linking architectural design to interactivity.

The start of a change in the way that design is made in architecture, through the tools created by engineering, is a fundamental element to emphasize the connection between all the parts of the article. Those tools have brought more than a simple change from analog to digital, bringing also the use of computation in architectural design with architects interacting with a computer and using programming languages, something that nowadays is used in parametric design, for instance.

This article targeted the research made to improve the design of industrial production for military purposes, revealing that a research project which intended to create a “drawing machine” made it possible the pioneering use of interactivity in architectural design research. That research has made architecture one of the first disciplines to research the digital interactivity on which nowadays smartphones and tablets depend.

Although digital interactivity took time to be a generalized architectural practice, the importance of architecture in the research of interactivity has contributed to the discipline’s pioneering role in the roots of 4IR.

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Crossing Timelines

Main research topics in the histories of eCAADe and SIGraDi

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Being in tune with the joint eCAADe and SIGraDi conference, this paper systematizes and analyzes data related to the set of papers presented in the history of the conferences of both societies. Which paths traced from eCAADe and SIGraDi brought us to the ``architecture in the age of the fourth industrial revolution''? This paper describes a bibliometric study focused on eCCADe and SIGraDi papers from 2003 to 2018 retrieved from CumInCad by using an open source software developed by the team for this research. The most used keywords and most cited authors, cross-citations between societies and time series about this data were synthesized, recovering part of the histories of these societies. Some similarities and differences between them are pointed out allowing to understand their past for better drawing their future.

Keywords: *CAAD, History, Bibliometrics, Cumincad, eCAADe, SIGraDi*

INTRODUCTION

As Walter Benjamin (1969 [1935]) wrote about the art in "the age of mechanical reproduction", every mode of production also generates human sensibilities that are related to it. Since Benjamin's work, the expression "X in the age of Y" has been used to distinguish some alterations in the modes of production and reception related to architecture and the arts in the face of technological, cultural, and economic transformations (Eisenman, 1994; Davis, 1995; Gumbrecht & Marrinan, 2003; Frampton, 2005, among others). Therefore, "architecture in the age of the fourth industrial revolution" is not only inserted within the lineage of references to the title of Benjamin's celebrated essay but also induces the investigation of sensibilities that have shaped this new condition of architecture. In this sense, a historiography of the concepts that make up an epistemological context becomes a relevant way for the understanding of this very context.

The introduction and evolution of computing in architecture in just over half a century is been accompanied by still recent historiography of this process. Authors have already focused on the emergence of architectural theories (Rocha, 2004), the evolution of the publications themes (Koutamanis, 2005) and the archeology of scientific conferences in the field (Celani & Veloso, 2015), among other topics.

Being in tune with the joint eCAADe and SIGraDi conference, this paper systematizes and analyzes data related to the set of papers presented in the history of the conferences of both societies, which have been, respectively, since 1983 and 1997, the main scientific forums on CAAD in Europe and Ibero-America.

Which paths traced from eCAADe and SIGraDi brought us to the "architecture in the age of the fourth industrial revolution"? Further on, are there similarities/differences in relation to the thematic approaches between both sisters societies conferences? What are the main topics covered by the papers throughout this period? Are there temporal asynchronies in approaching these topics? Are the main references cited in the papers coincidental and/or express local specificities?

METHODS

Bibliometrics was used for this study, seeking for metric indicators derived from scientific publications to verify research trends, using the eCAADe and SIGraDi papers published in CumInCAD digital library between 2003-2018 as a sample universe. The choice of this period of time is justified below. Pritchard (1969, p. 349) defined bibliometrics as " [...] the application of mathematics and statistical methods to books and other media of communication", Fairthorne (1969, p. 319) paraphrased as "quantitative treatment of the properties of recorded discourse and behavior appertaining to it."

To retrieve the bibliometrics data from eCAADe and SIGraDi was developed an open-source software in Python, named WSB (Figure 1), that reads the HTML code of CumInCAD, available on <https://github.com/ezambomsantana/web_scraping_bibliometrics>. In this site, it is possible to generate a page with all the metadata from all the articles for a conference and a year range. After reading this data, we created tables with the keywords and references of all the papers. Then, we could group and aggregate the data creating different information about the conferences such as the most cited keywords and authors by year.

```
91 lines (72 sloc) | 3.66 KB

import requests
import pandas as pd
import matplotlib.pyplot as plt
from bs4 import BeautifulSoup
import sys
import re
import networkx as nx
import functions as f

folder = "/home/eduardo/sigradi/"

keywords = f.get_synonyms(folder + "key - eCAADe.csv")

url_ecc = "http://papers.cumincad.org/cgi-bin/works/Search?search=&paint=on&f%3

G = nx.Graph()

keyword_year = []
conf_year = []
authors_ref = []
authors = []
year = 0
keys = []

for artist_name in f.get_page(url_ecc):

    header = artist_name.find("th")
    data = artist_name.find("td")

    if header.contents[0] == 'year':
        year = data.contents[0]

    if header.contents[0] == 'keywords':
        kws = data.contents[0].replace(',',';').replace('/',';').split(';')
        for k in kws:
            if k != '':
                if k.strip().lower() in keywords:
                    k = keywords[k.strip().lower()]
```

Figure 1
Detail of the WSB code

CumInCad is an acronym for CUMulative INdex of CAD created in 1998 as a repository of scientific information in the field of CAAD (Martens, Turk, 2000; 2003), upgraded to free access in 2015. Its main goal is "(1) to build a 'collective memory' of scientific publications from conference proceedings of CAAD-associations; and (2) to make this memory unconditionally accessible to the scientific community as a web-based bibliographic repository of works" (Cerovsek & Martens, 2016: 485). In previous work, Cerovsek and Martens (2004) have already presented an extended review of this repository showing its potential as a resource to the researches in the field of CAAD. They analyzed the chronological distribution of CumInCad references; frequency, distribution, age, year-to-year distribution between citations; distribution of citations per number of authors. Some examples of author-citation networks and a list of the 25 most cited authors by the 6399 records retrieved in the repository in 2004 were presented as well.

A comparative study focused on data from papers of specific societies retrieved from CumInCad has not yet performed. From the 14386 entries found in CumInCad (June 2018), we retrieved data from 4009 papers, which corresponds to 28% of the total entries. This sample corresponds to 2095 papers from eCAADe and 1914 papers from SIGraDi.

The methodology of our research is structured by the following steps: 1) data entry of the general themes of the annual congresses of each sister society (eCAADe / SIGraDi); 2) collecting keywords from all papers; 3) data tabulation of the 10 most used keywords by each sister society papers per year; 4) selection of papers that use the prevailing keywords in each sister society per year; 5) data entry of bibliographic references most used by papers selected in each sister society per year (at least three citations); 6) pre-analysis of the data obtained by society and by year (keywords and bibliographic references); 7) crossing of collected data (eCAADe x SIGraDi); 8) generation of diagrams and timelines with the data of each society and by crossing data; 9) analysis of data.

One limitation of the methodology is some missing data in CumInCad. For SIGraDi, from the 2313 papers from the period 1998-2018, 30% do not have the keywords or the references in the metadata. This problem was minimized in the last years, as from 2009 to 2018, only 15% of the papers do not have the keywords or the references. Regarding eCAADe, there are also some missing data. From the 2528 papers, 15% of them do not have the keywords, and 8% do not have the references in the metadata. About SIGraDi, the templates from 1998 to 2002 and 2005 have not keywords or the keywords have not metadata. About eCAADe, the year 2002 has not metadata for the keywords.

The period initially defined to run this study was 1998-2018, considering the first year of SIGraDi papers available on CuminCad. But, due to these inconsistencies, the period of the study was changed to 2003-2018. Even for this period, some observations should be done. SIGraDi 2005 was not considered in the study because there is no metadata of keywords. SIGraDi 2004 was not considered in the references study because there is no metadata about them. eCAADe 2015 was not considered from the references study because there is no metadata of keywords in Cumincad and the software we developed needs them in the system to retrieve the references. In this case, keywords were collected by hand for allowing the most completeness of the study. Table 1 shows the number of papers from eCAADe and SIGraDi per year in Cumincad.

Table 1
Number of Papers from eCAADe and SIGraDi per year (2003-2018)

Year	eCAADe	SIGraDi
2003	104	131
2004	82	126
2005	102	140
2006	134	96
2007	116	88
2008	118	23
2009	107	142
2010	96	103
2011	112	125
2012	158	151
2013	152	129
2014	132	135
2015	155	121
2016	146	149
2017	169	101
2018	212	154
Total	**2095**	**1914**

RESULTS AND DISCUSSION

The results of the study are systematized below in three topics: 1) conferences themes; 2) top ten keywords; 3) most referred authors and cross-citations.

Year	eCAADe	SIGraDi
2003	Digital Design	Digital Culture and Differentiation
2004	Architecture in the Network Society	The Meaning and the Digital Universe
2005	Digital Design: the quest for new paradigms	Vision and Visualization
2006	Communicating Space(s)	Post-Digital: the human factor
2007	Predicting the Future	Communication in the Visual Community
2008	Architecture "in computro" - Integrating Methods and Techniques	Digital Graphics and Applied Computing: cooperation, integration and development
2009	Computation: The New Realm of Architectural Design	From Modern to Digital: challenges of a transition
2010	Future Cities	Disruption, Modeling and Construction: changing dialogues
2011	Respecting Fragile Places	Augmented Culture
2012	Digital Physicality | Physical Digitality	Form(in)formation
2013	Computation and Performance	Knowledge-based Design
2014	Fusion	Design in Freedom
2015	Real Time	Project Information for Interaction
2016	Complexity & Simplicity	Crowdthinking
2017	Sharing of Computable Knowledge! – ShoCK!	Resilience Design
2018	Computing for a Better Tomorrow	Technopolitics

Table 2
Conferences
Themes
(2003-2018)

Conferences Themes

The eCAADe and SIGraDi conferences use to have main themes from which they intend to converge knowledge interchange and discussions on CAAD and relate topics. Table 2 shows the conferences' themes of both societies for the 2003-2018 period. A deep analysis of them is not an object of this paper, but in general, the themes are compound by concepts, statements or actions related to the expanded field of CAAD. These themes seem to indicate aspects of global order, linked to the globalized digital context, and aspects of local order, linked to specific forms of insertion in the global debate.

Top Ten Keywords

Using the WSB open-source software developed for this study, we found 8574 entries for keywords in papers of eCAADe conferences and 5888 entries for keywords in SIGraDi. As the template of SIGraDi 2005 has not keywords, the corresponding papers, their data were not retrieved. As keywords have recurrence, the number of keywords are 5058 and 3327 respectively. This sample shows that eCCADe sample is 1.52 the SIGraDi sample. After the keywords in each paper were tabulated, and the ten most frequently used keywords in the entire period and in each year were highlighted. Table 3 shows the frequencies of the top ten eCAADe and SIGraDi keywords for the entire period.

Data retrieved in CumInCad	eCAADe	SIGraDi
Number of papers	2095	1914
Keywords in the sample	5058	3327
Total of keyword entries in the sample	8574	5888 (*)

** The SIGraDi 2005 template has not keywords.*

Table 3
Keywords
Occurrence in
eCAADe and
SIGraDi (2003-2018)

The eCAADe and SIGraDi shared 6 keywords from their top ten: parametric design, digital fabrication, bim, virtual reality, shape grammar and design process. Still in the top ten, the other eCAADe keywords were: urban design, generative design, collaborative design and simulation; for SIGraDi the other keywords are: heritage, architectural design, interaction and cad.

The general results show that the top ten keywords had a big frequency in the whole sample of keywords of both societies, making a total of 46.8% of the keywords used in eCAADe and 36.2% of keywords used in SIGraDi.

Considering the use of keywords throughout the years, there are some interesting dynamics to point out. The keywords design fabrication and parametric design became strong terms in both societies from 2006, even if the last one appeared before in eCAADe in 2003. Together with BIM, that appeared among the top ten keywords from 2007 in both societies and generative design appeared in eCAADe from 2006, these keywords indicate some of the main research topics in more than a decade. Simultaneously to the strengthening of these topics, 3D modeling and animation started to be outside of the top ten keywords for both societies in 2009. The correlation of these facts exposes a relevant turning point to the research in CAAD from those years.

Another interval to highlight is 2013-2016 when computational design (2013), robotic fabrication and 3D printing (2015) began to be inside the top ten in eCAADe, and virtual reality (2016) reappeared in both societies after being between the top ten between 2003 and 2010. In the period, collaborative design (2013) and education (2015) left the list of top ten keywords of eCAADe and design process (2015) left the same list for both societies. These alterations, if maintained, could indicate another relevant shift to the research in CAAD in the near future.

Both societies shared emphases on the keywords design process (2003-2015) and shape grammar (2005-2018) throughout the period. For the eCCADe side there are emphases on collaborative design (2003-2013), generative design (2006-2018), computational design (2013-2018), urban design (2010-2018). For the SIGraDi side were found emphases on the use of digital tools for heritage (2004-2018), interaction (2011-2016). Other keywords used appeared in SIGraDi conferences had not prevalence in more than two years, indicating a distribution of occurrences of many keywords. A timeline was drawn to turn visible these dynamics among research topics (Figure 2). The whole image is available at <https://drive.google.com/file/d/1w2mtoZ2iDZU-J7sU1j1yulDPUbtGV1o3/view?usp=sharing> (Top of the image).

Most Referred Authors and Cross-citations

From the lists of top five keywords per year in each society, the papers of the sample that mentioned at least one of these keywords had their references retrieved. The top ten authors cited in eCAADe and SIGraDi for that keywords are listed in Table 5. Taking into account the period from 2003 to 2018, eCAADe and SIGraDi share 5 among the 10 most referred authors in their conferences for those keywords. While in eCCADe the top ten referred authors are from the

Figure 2
Detail of the timeline of main research topics in eCAADe and SIGraDi according the years (2003-2018)

eCAADe Number of papers: 2095 (*)			SIGraDi Number of papers: 1774 (*)		
Keywords	**n**	**%**	**Keywords**	**n**	**%**
parametric design	184	8.8	parametric design	137	7.7
digital fabrication	135	6.4	digital fabrication	134	7.6
bim	117	5.6	bim	79	4.5
urban design	92	4.4	heritage	58	3.3
virtual reality	91	4.3	design process	50	2.8
generative design	85	4.1	architectural design	44	2.5
collaborative design	83	4.0	shape grammar	40	2.3
shape grammar	80	3.8	virtual reality	37	2.1
design process	57	2.7	interaction	32	1.8
simulation	57	2.7	cad	28	1.6
Total	**981**	**46.8**	**Total**	**639**	**36.2**

** Obs. (1) The keywords "architecture" and "design" were considered as qualifiers and were excluded of the sample. (2) Papers from SIGraDi 2005 were excluded due to the lack of keywords.*

Table 4
Frequencies of eCAADe and SIGraDi Keywords (2003-2018)

eCAADe Total of references: 262		SIGraDi Total of references: 115	
Authors	Citation frequencies	Authors	Citation frequencies
duarte, j.	98	kolarevic, b.	54
stiny, g.	76	eastman, c. m.	35
fioravanti a.	44	duarte, j. p.	31
eastman, c.	42	oxman, r.	29
kolarevic, b.	36	celani, g.	25
menges, a.	33	herr, c. m.	20
mitchell, w. j.	33	kohler, m.	18
beirão, j.	32	gramazio, f.	17
kohler, m.	32	sacks, r.	17
gramazio, f.	31	borda, a.	16

Table 5
Top ten authors cited in eCAADe and SIGraDi for the top five keywords (2003-2018)

Global North, in SIGraDi only two of the most referred authors are from the Global South, Gabriela Celani and Adriane Borda. Other significant difference is the frequency with which each reference was mentioned in these two societies. Among the top ten authors, Branko Kolarevic is the only one who is more cited in SIGraDi than in eCCADe, while the other authors have more citation frequency in eCCADe (See Table 5).

In the next step, authors referred at least three times for a keyword per year of each society were retrieved. In the eCAADe, 262 authors were mentioned at least 3 times, while in the SIGraDi, 115 authors followed the same criterion. From them, only 20 authors are coincident in papers of both societies. Among the other authors cited there are a recurrence of regional and local citations that will be subject of a future study.

Another analysis performed was focused on topics that had authors cited at least 3 times in both societies in the same year, looking for similarities and differences between main topics of both societies (See table 6). The keywords found under this criterion were: digital fabrication, parametric design, BIM, virtual reality and urban design. Then, the top ten authors for each keyword were selected. Among them, there were authors referred to in papers related to several keywords. José Pinto Duarte was cited for digital fabrication, parametric design and urban de-

Table 6
Top ten authors for main topics - keywords with authors cited at least 3 times in both societies in the same year (2003-2018)

DIGITAL FABRICATION			
eCAADe	**n**	**SIGraDi**	**n**
kohler, m.	25	kolarevic, b.	25
gramazio, f.	24	kohler, m.	18
kolarevic, b.	17	herrera, p.	17
duarte, j. p.	14	gramazio, f	14
menges, a.	10	sass, l.	10
oxman, r.	10	sperling, d. m.	10
sass, l.	9	paoletti, i.	9
mitchell, w. j.	7	oxman, r.	8
pottman, h.	7	celani, g.	7
iwamoto, l.	6	naboni, r.	7

BIM			
eCAADe	**n**	**SIGraDi**	**n**
eastman, c. m.	34	eastman, c. m.	35
kalay, y. e.	17	sacks, r.	17
sacks, r.	17	liston, k.	6
fioravanti a.	15	succar, b.	6
simeone, d.	13	teicholz, p	6
teicholz, p.	12	ruschel, r. c.	5
trento a.	8	von hippel, e.	5
liston, k.	7	aish, r.	4
loffreda, g.	7	amorim, a. l.	4
yan, w.	7	checcucci, e. de s.	4

VIRTUAL REALITY			
eCAADe	**n**	**SIGraDi**	**n**
schnabel, m. a.	12	timmermans, h.j.p.	4
kvan, t.	10	ames, a. l.	3
charitos, d.	7	glanville, r.	3
knight, m.	6	linzer, h.	3
wössner, u.	6	moreland, j. l.	3
dalton, r. c.	5	musse, s. r.	3
dias, m. s.	5	nadeau, d. r.	3
hölscher, c.	5	russell, p.	3
dokonal, w.	4	sutherland, i. e.	3
dorta, t.	4	voigt, a.	3

PARAMETRIC DESIGN			
eCAADe	**n**	**SIGraDi**	**n**
menges, a.	18	kolarevic, b.	19
woodbury, r.	17	oxman, r.	14
stiny, g.	14	borda, a.	10
oxman, r.	12	celani, g.	9
hensel, m.	10	hillier, b.	9
duarte, j. p.	9	woodbury, r.	9
janssen, p.	9	duarte, j. p.	7
kolarevic, b.	9	mitchell, w. j.	6
pottman, h.	8	sass, l.	6
stouffs, r.	8	terzidis, k.	6

URBAN DESIGN			
eCAADe	**n**	**SIGraDi**	**n**
duarte, j.	24	duarte, j.p.	5
beirão, j.	16	schmitt g.	5
stouffs, r.	10	abdelhameed, w.	4
schmitt, g.	9	kobayashi, y.	4
waddell, p.	9	müller, p.	3
gil, j.	7		
van gool, l.	7		
zupancic, t.	7		
montenegro, n.	6		
haegler, s.	5		

Table 7
Number of Cross-citations between papers from eCAADe and SIGraDi

Year	eCAADe papers in SIGraDi papers	SIGraDi papers in eCAADe papers
2003	8	8
2004	0	4
2005	12	8
2006	4	7
2007	12	6
2008	14	7
2009	22	4
2010	10	7
2011	7	3
2012	6	8
2013	16	6
2014	28	5
2015	16	8
2016	27	3
2017	12	5
2018	34	8
Total	**228**	**104**

sign. Branko Kolarevic, Achim Menges, Rivka Oxman, Lawrence Sass, William Mitchell and Helmut Pottman were cited for digital fabrication and parametric design. Rudi Stouffs was cited for parametric design and urban design. The other authors were associated with only one keyword.

Some similarities with the citations for the top five keywords were found here. While in eCCADe the top ten referred authors are from the Global North, in SIGraDi only seven of the most referred authors are from the Global South, Pablo Herrera, Gabriela Celani and David Sperling for digital fabrication, Adriane Borda and Gabriela Celani for parametric design, Regina Ruschel, Arivaldo Amorim and Érica Checcuci for BIM. Gabriela Celani is the only author of SIGraDi most cited for two keywords in SIGraDi itself.

Looking for other interrelations between both societies, a cross-citation study was performed. The results indicate that eCCADe papers are more cited in SIGraDi than the opposite (See table 7). One among other inferences that can be made for this difference is that most of the SIGraDi papers were written in Spanish and Portuguese. On the other hand, there were a significant number of intra-region citations, that is, eCAADe papers were cited by other eCAADe papers, and SIGraDi papers were cited by other SIGraDi papers. An extensive network of authors and their origins, languages and citations will be subject for a further study.

Cross-citations

In order to synthesize much of this paper's data, another timeline was drawn to allow visualizing information as conference themes, top five keywords, authors with at least three mentions per year, the number of citations per author along the years (Figure 3). The whole image is available at <https://drive.google.com/file/d/1w2mtoZ2iDZU-J7sU1j1yulDPUbtGV1o3/view?usp=sharing> (Bottom of the image).

CONCLUSION AND OUTLOOK

The study carried out from the most cited keywords and most referenced authors captured processes of consolidation and change of research topics. This methodology can not point to the first occurrences in relation to time series but captures these processes when they incorporate a larger critical mass, as shown in the timelines (Figures 1 and 2). These timelines show how consolidation processes and disruptive moments are produced collectively by an extensive community of researchers, which even exceeds the two societies.

The WSB open-source software developed proved to be an excellent tool for retrieving information from Cumincad metadata. New increments are being considered to create an interface for displaying the data in the form of timelines and networks.

The data analyzed show differences and similarities between eCAADe and SIGraDi. The former clearly shows a stage of maturity, while the later shows a process of growth and strengthening of its performance. The growth of a group of authors most cited in recent years in the SIGraDi conferences, as well as the similarity of the main research topics with eCAADe, show its insertion in a global context of research. A contribution to a greater connection between the productions of both societies, and to a greater impact of the papers presented in SIGraDi and made available by CumInCad, would be the adoption of English. While some research topics appeared simultaneously among the top ten keywords in both societies, such as digital fabrication and parametric design, others are still far from this level as computational design and robotic fabrication. Factors not treated in this study, economic ones and others relative to the context of the civil construction, are decisive to understand this challenging scenario for innovation.

It is expected that the visualization and analysis of data extracted from papers presented in the eCAADe and SIGraDi between 2003 and 2008 could contribute to the mutual understanding about part of the history of emphasis given to research by the

Figure 3
Detail of the timeline of top five keywords and most referred authors per year in eCCADe and SIGraDi (2003-2018).

participants of these sister societies, which significantly contributed to the scientific knowledge in the CAAD area over the last two decades. Returning to the introduction of this paper, we believe that the way perception is organized depends not only on human nature and the historical context, as Walter Benjamin stated. From a contemporary view anchored in Gilles Deleuze (1995 [1968]), the perception of the present time is only shaped by the understanding of different coexistences that make it up.

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CoDesign Spaces

Experiences of EBD research at an industrial design makerspace

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During the last years, insertion of technology accelerates its incursion both in the design process and in the teaching-learning process. Design education has gone through different visions: Some hold the vision of education in design with a look at professional training. Others, have chosen to study the roots and problems of the training process, the ultimate goal is to generate experts in future designers. An element that - consistently - is often absent from such discussions is the role played by prototypes in the teaching-learning process. This research reviews the role that the prototype has played, as a central element, in the process of collecting evidence, with a view to informing the decision making during the development of Project Design. The paper discusses the role that prototypes - from the standpoint of CoDesign, Evidence Design, and evolutionary design - have played in the teaching experiences of the last four semesters within a Computer Lab for students of Industrial Design. The systematization of information extracted from the research experiences has evolved from the Lab model to the Maker-space experience.

Keywords: *Prototype, FSB Framework, Makerspace, Industrial Design*

INTRODUCTION

This paper reports an educational experience carried out with Industrial Design students - junior and senior levels - at the University of Chile. The paper summarizes our experience after three years running a seminar in design computing. Such an experience has evolved from the Lab model to the Maker-space experience. In this paper we revise the overall experience and discuss the integration of three frameworks that have driven the navigation of the course. Further, lessons learned at sight of the integration of these models and its implications for design education are discussed at the end of the article.

BACKGROUND

AT university of Chile, industrial design students' work in the seminar in Design Computing, which last 38 weeks and is divided in two semesters of eighteen weeks each, in their junior and senior years.

This seminar establishes student's first approach to the use of research methods. The goal of the seminar is to build a link between design formulation, design problem solving, and digital fabrication with special focus on two topics. First, research methods that provide students with empirical evidence to guide their decision-making processes and second, the role that the prototype play in the collaborative process of framing their proposals.

The concept of prototype, for Sanders and Steppers, emerged historically as a "means to give life to ideas before they are built or manufactured". However, just as current design frontiers are undergoing radical changes, so are the prototypes and activities carried out with prototypes (Sanders, 2013). This change lies in the fact that prototypes nowadays become a participatory element which allows engagement of designers and community. Further, Sanders and Steppers claim that design happens in communities made up of users. These communities trigger the emergence of creative activities for non-designers, and the interest in Design Thinking by people linked to business and with the obsession of -create / co-design by various actors. We put students under this precedent, and impulse them to interact with real case users, gather evidence about their users experiences, and reflect on the role that the prototype plays in such processes.

THREE FRAMEWORKS

In this experience we have overlapped three different frameworks. One for triggering thinking on the role played by the prototype, other used to frame the design problem and track their own design process. Lastly, we introduce an approach to gather - and reflect on the role that - evidence plays in their design processes. These three models are presented below.

Make-Tell-Enact: the role of the Prototype in the participatory prototyping cycle (PPC)

The prototype, under the traditional model of education in design, was usually a model of representation, of high visual fidelity and low level of functionality, present in final stages of design processes with the aim of transmitting to the client the final appearance of the product.

Thus, the "traditional" prototype allows, according to Sanders (2013), Dorst (2015) and Stappers (2013):

- Experiment or explore ideas
- Identify problems
- Understand and communicate form or structure
- Overcome the limitations of two-dimensional representations
- Support the testing and refining of ideas (concepts and principles)
- Communicate with others and
- Finally, we sell the idea to another.

These functions, Sanders clarifies, work according to the iterations in the design stage in which is the opera prototype. Starting from these ideas, Sanders proposed a change in the role that prototypes ought to play, shifting the focus of attention to the experience, the people, the revision, and the learning process. Thus, new roles that the prototype can play emerge. Such roles gather "research with new functions" (Dorst, 2015; Sanders and Stappers, 2014; Stappers, 2010). Consequently, the prototypes serve to:

- Evoke focused discussions in the research team.
- Test hypothesis
- Confront theories given their ability to force the superposition of different perspectives/theories and frames of reference and
- Allow people to live a situation that did not exist before.

Sanders establishes three key states that guide collaborative design processes; make, tell, and enact. Make refers to the fabrication process of working models as well as the final model. The devices made by students when framing their research focuses on describing user experiences and the final models seek to represent the final design along with all its details. Tell enhance gathering preliminary information and testing out hypothetic scenarios, which triggers the exploration of more research questions. Enact refers to interacting with the prototype in such a way that students obtain the user experience information; achievements, difficulties, and background information that allow users to participate in the co-design process.

According to Sanders, the participatory prototyping cycle can be entered at any of the states described above, which does not follow a linear order. Thus, participation of team members as well as interaction with real user are documented in the search for relevant and empirical information looking for "helping students gain critical problem-solving and inquiry skills in the context of relevant, real-world, interdisciplinary problems." (Honey & Kanter, 2013).

Framework FBS (Function - Behavior - Structure):

The Function-Behavior-Structure framework introduced by Chandrasekaran () and expanded by several scholars (), particularly Gero in design (), conceptualizes design in three ontological categories: function (F), behavior (B), and structure (S). The ontology models design processes a set of activities which in turn are related to any of the categories. In the ontology, function captures the purpose that the design goal must accomplish. The behavior gathers the set of attributes derived from the design structure. The structure, on the other hand, represent the components of the design object itself and its relationships. Figure 1, below, present the FBS diagram made by a group of students after accomplishing the first task of the course, which is to succeed at the "egg challenge game". Students must design and fabricate a structure to drop off and egg from 12-meter-high and the egg must "survive". The diagram renders the FBS model of their designs.

Afterwards, students are asked to present an FBS diagram of the design problem that emerges from interviewing real users and real problems, which are the base of the semester design project.

Evidence Based Design (EBD)

Evidence-based design, (EBD) is defined as the process of basing decisions about the built environment on credible research to achieve the best possible outcomes. The current definition spans numerous disciplines, including architecture, interior design, landscape design, facilities management, education, medicine, and nursing. We use this definition to enhance student to base their design decisions process on the evidence they collect along their interactions with the users of their prototype. Students must present in posters or presentations the links they made between the evidence collected and the information provided by the users. Such posters and presentation must have graphical depictions and photographs as the constituent elements of their evidence.

The makerspace

This research reviews the role that the prototype has played, as a key feature, in the process of collecting evidence, while interacting with team members and real users. Students use such an evidence to inform their design decision making processes.

The systematization of information extracted from the research products developed by the students, that is, posters, presentations, reports based

Figure 1
Example of the FSB Ontology applied by students to the "egg challenge" design problem.

on a research problem and the design of their prototypes, is considered the main input for the development of this work.

To carry out this study, we analyze 19 design projects produced in 4 iterations of a class in our undergraduate design program.

Thus, the class has become a laboratory to look at the evolution of the role that the prototype has played in students understanding of its nature.

To carry out the evaluation, we followed the model proposed by Sanders & Stappers (2014), which includes the crossing of five dimensions and three analysis units, focusing on the role that the prototype acquires in the stages of pre-design, generation, evaluation, and post-design.

Additionally, our analysis contemplates the comparative review of the results obtained from the Sanders & Stappers model, with the methodological tactics informed by the participants of the group course in the posters and academic articles produced with the prototypes.

Tactics used by students in their research and design processes

1. The first key step that students face is the formulation of their "design research problem"
2. Several students, in the initial stage of their projects, seek relevant information

Not all approaches to the determination of this instance should be charged or expressed of the negativity that the word problem seems to imply.

Many of the students, in the initial stages of their projects, look for a lack, problem or difficulty and often see superficially, speculatively and lacking relevant background approaches to the design problem (which should be thought of as an opportunity, improvement).

In this way, it is important to understand and clarify ways in which prototypes deliver relevant information even for the discovery of a possible problem.

This makerspace implements initial stages of prototype development with a view to developing research with strong information backup.

DISCUSSION AND LESSONS LEARNED

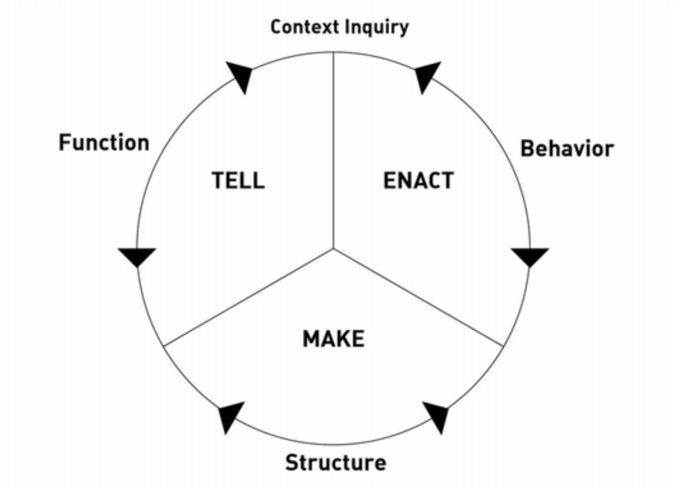
We envision four main lessons so far:

1.- The change in the role that the prototype play in students design processes. As the students were involved in their projects, they reaffirmed that prototyping does not refer exclusively to the final stages of Design. An important part of the results was favored by the high functionality of the prototypes that, as the investigations iterated, each team found strengths that developed autonomy, confidence, and validation with respect to the information that the different prototypes, the interaction with the users and the participation of contexts and actors gave them.

2.- Moving from a Laboratory to a Makerspace: The demands of implementing methodologies such as this not only generate changes in the teaching-learning process, but also change the appropriate spaces for the realization of each of the projects. During the experiences lived these four semesters, have been more favorable for each project to have training spaces where you can manufacture, experiment and submit to evaluation each of their prototypes. The initial semesters, when it was decided to use laboratories exclusively with computers, limited these approaches, making the design and development of the projects difficult, as well as the meeting spaces between the teaching team and the students.

3.- The integration of methodologies for the development and evaluation of prototypes such as PPC and FBS which are powerful tools that together allow evaluating, validating and improving the degree of decision making in prototypes developed by students. As a recursive and iterative process, Evidence-Based Design is not based exclusively on one of these models, it is when they interact with each other that each of the stages of the investigations can be explored in greater detail, generating reflective spaces in the students through action. and experimentation: The validation of techniques for the development of new technological spaces.

Figure 2
Render the overlap structure of the Make - Tell - Enact and Function - Behavior - Structure frameworks.



4.- For the instructors team, this type of changes poses new challenges from the point of view of implementing multidisciplinary training spaces to effectively generate a co-design environment where other disciplines can bring themes, provide different approaches and understand the design processes; we do not rule out opening this type of instances to training spaces interacting with Computer Engineers, Architects and Designers.

The motto of the class is that digital technologies are a mean to develop and evaluate both design products and user experiences. In particular, the course focuses on exploring the insertion of technology in design research.

This experience, we expect, should facilitate the irruption of the new role that Sanders envision for the prototype. Hence, we expect - and move towards - a change in student´s world view and favor their interest in exploring design decision making based on the use of evidence.

So far, we have observed an increase in the development of autonomy and collaborative work of the working groups based on the design of prototypes and the information extracted for the iterations during the development of the project. Thus, students respond to real-world problems in the context of the ethos of the class and by using the selected frameworks. Figure 2 show how such frameworks overlap. Further, they go through hands-on learning experience even though they are not accustomed to it. Moreover, they discuss the role of the prototype in their design process as well as the use of the evidence collected by them and their users.

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Trend Topics and Changing Concepts of Computational Design in the Last 16 Years

A content analysis

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This study argues that analysis of written content might be helpful to provide clues at a certain extent on the future directions of current research areas and the emergence of new study areas. In the scope of the study, the International Journal of Architectural Computing (IJAC) which has been a scientific platform covering many pioneer publications on education research in computer-aided architectural design (CAAD) field was selected as source content. Although the size of the source domain is limited, the analysis of abstracts and titles of 439 articles published in IJAC between 2003 and 2018 revealed promising results which can be examined under four characteristics: ``constant'', ``emerging'', ``fading'' and ``solidifying'' concepts. The tokens in the analysis process are words, phrases, topic nodes and links between topic nodes. The outcomes of this study might contribute to tracking the evolution of concepts their emergence or disusage in different time and contexts, and interrelations between different concepts.

Keywords: *content analysis, computational design concepts, IJAC*

INTRODUCTION

The reflection of digital technologies on theory and practice of architectural design has been discussed over the last two decades. Widespread usage of personal computers, changes in the way the architectural knowledge is represented, decoded, reproduced and shared through digital media have been on the way architects think and design. Not only the hierarchical organization of the architectural offices but also the terminology, concepts, and description of methodologies have been evolving relatedly. With the impact of technological changes, the transformation in architectural design practice has led to the emergence of new concepts, and some of the existing concepts have started to convey new meanings. In that sense, spoken or written language has the potential to provide indicators about the direction of changes and transformations. The indicators which can be captured from discourse should be considered as an anchor or focal points of transformation, which do not cover all aspects and dimensions of the technological transformation in architectural design practice.

This study aims to provide an interrelation map on the computation concepts reflected into the architectural design field, through analysing keywords, concepts, and phrases in the published media. As de Sola Pool (1959) underlines the limitations of word-based content analysis in the extraction of meanings of any context, it might still have the potential to provide insights on cause-effect relationships. Taking the difficulties of content analysis method in mind, the motivation of the study is derived from gaining more insights into the potential patterns embedded in the changing concepts of computational design domain. The main elements of the pattern searching process are considered as words, phrases, topic nodes, and links among topic nodes. Based on these assumptions, this study aims to investigate whether it is possible:

- to extract trend topics based on the frequency of the words and phrases;
- to find distinctive characteristics of topic nodes;
- to make predictions on the direction of change and characteristics of topic nodes;
- to make inference about the emergence of new methods, tools, approaches and their reflection onto scientific studies based on the content analysis of a given text.

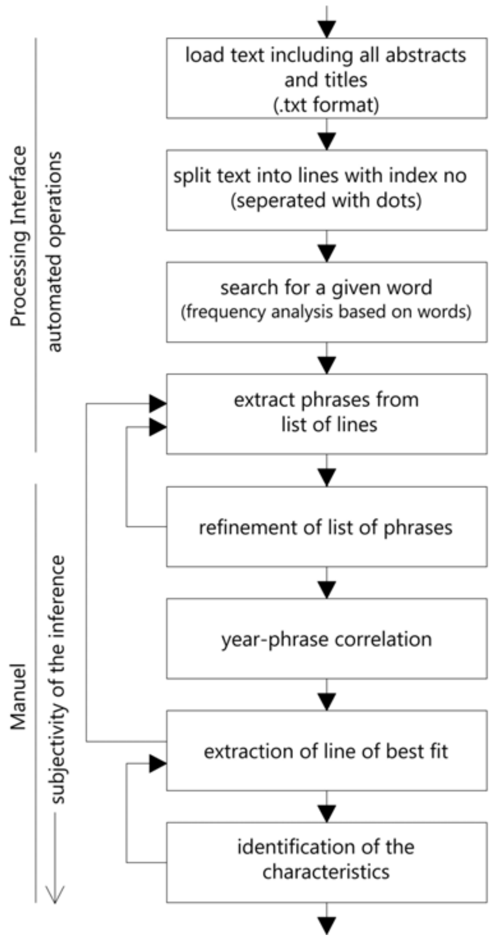
In the scope of this study, the abstracts and the titles of the peer-review articles in the International Journal of Architectural Computing (IJAC) between 2003 and 2018 were used as a source of data. The abstract of 439 articles in 63 issues which were published in a 16 years period was analysed. Although there have been various conferences on CAAD which made it possible for the people from universities, practice and industry to encounter and gather since 1960s (Celani and Veloso, 2015), accumulating the experience of sister conferences such as eCAADe, ACADIA, SIGraDi, ASCAAD, CAADRIA, and CAAD became a distinctive advantage for IJAC to provide a common ground for opening new debates in theory and practice. This study introduces a content analysis method to be used in the analysis of concepts and trend topics of CAAD. Four main characteristics are explored in the initial analysis process: constant, emerging, fading and solidifying concepts. Further to the association of the explored characteristics with time and frequency values, it is observed that the proposed method has potential to become an analysis tool providing a basis for different readings of the given text and contexts.

RELATED STUDIES

The term discourse is defined as “a particular way of talking about and understanding the world or an aspect of the world” by Philips and Jørgensen (2002). As an umbrella term, the discourse has been approached by people from various fields such as philosophy, psychology, sociology, linguistic or political science in different axes and extends. As a common denominator, discourse analysis refers to the analysis of language or language-like structures to extract new relations, patterns or frames (Philips and Jørgensen, 2002). Relational topic models are well-established methods (Chang and Blei, 2009; Marcin and Shiu, 2012) both analyzing a larger amount of data and extracting relations from the source content. Another approach, the critical analysis concerns the demystification of social context through using written or spoken language. Regarding the reflection of technological advances into architectural practice and discourse, what one calls novel easily becomes common and acquaintance in a short period of time. On one hand, new concepts have been emerging, on the other hand as a living organism the meaning and impact area of an existing concept is being transformed continuously.

In relation to the concepts, topics, and approaches of computer-aided architectural design (CAAD), remarkable literature has started to be accumulated with an increasing acceleration since the early 1990s. Apart from the widespread use of digital technologies in architectural design, the written culture involving books, conference papers, and articles have also contributed to expanding the knowledge in the digital design field. As an instance, the web-based database, Cumulative Index of CAAD (CUMINCAD.SciX.net) has provided a common plat-

Figure 1
Flowchart of the proposed methodology



form for academicians, practitioners, and students since 1998. When it came to 2003, in the second issue of IJAC, Martens and Turk mentioned the necessity of a systematic approach to categorize, store and recall the information in the growing body of CUMINCAD database. Martens and Turk (2003) provided a provisional list of 30 keywords to be used in indexing the CAAD related concepts. Celani and Veloso (2015) presented a comprehensive overview of the history of CAAD, tracing back to the theoretical studies in the 1960s and focusing on the conferences between 1980s and 2015. Investigating the trends, topics, concepts of conferences related to CAAD, Celani and Veloso (2015) introduced the most frequent keyword index used in CUMINCAD database. Liu et al. (2017) presented a domain-specific analysis of BIM concepts in bibliographic records and their evolution, examining 1874 BIM-related articles. Liu et al. (2017) unfolded thresholds and periods and their relationship with BIM-related concepts. Turk and Cerovšek (2003) underlined the similarities between computer-based understanding of two-words phrase selection and human intervention-based selection approach and suggested machine learning techniques as a leading future direction. At some extent, this study can be considered as an attempt to revisit the topic map of Turk and Cerovšek (2003), based on an extended and updated source of data. In addition, it will provide a comparison opportunity between Martens and Turk (2003)'s provisional list published in the second issue of IJAC and the new list extracted from IJAC database.

METHODOLOGY

The proposed content analysis method involves four steps (Figure 1): (i) quantitative analysis (frequency of word and phrase), (ii) frequency mapping (year-phrase correlation), (iii) qualitative analysis (characteristics of concepts), (iv) relational mapping (topic nodes and links).

Apart from the list of 30 keywords derived from CUMINCAD database presented by Martens and Turk (2003), 27 keywords were given by Celani and Veloso (2015) as the most frequent keywords found in CUMINCAD's keyword index. In the qualitative analysis process, not only Martens and Turk (2003)'s and Celani and Veloso (2015)'s keywords were used but also new words are added by the authors. As a result of human intervention based and computer-based word extraction processes (Figure 2; Figure 3), 60 keywords are chosen to be investigated in further steps.

$$\textit{List of Keywords} = \sum_{1}^{n_1} k + \sum_{1}^{n_2} k + \cdots + \sum_{1}^{n_3} k - O_k$$

list of keywords taken from the literature		frequency based selection
Martens & Turk 2003	Celani & Veloso 2015	IJAC 2003-2018
$n_1 = 30$	$n_2 = 27$	$n_3 = 60$

n: number of keywords O k: number of overlapping keywords
k: keywords

Figure 2
Calculating the overall number of keywords

The quantitative analysis process is simply based on word and phrase extraction from the source content depending on their frequency. Further to machine-assisted word extraction (Url-1), Processing interface was used for more precise calculations. The source content is titles and abstracts of the selected 439 articles which were published in IJAC between 2003 and 2018. Frequency mapping is the scatter plot representation of phrases in year (x) and frequency (y) axis. The third step use frequency mapping as a layout to determine trend lines (line of best fit) (Figure 4).

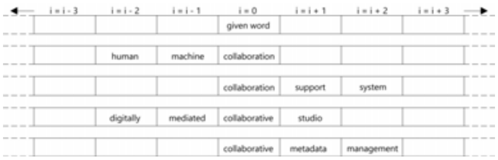


Figure 3
Adjacency based phrase extraction from the string lines

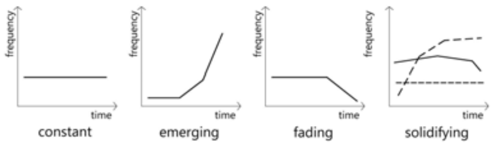


Figure 4
The main characteristic trends appeared in the year-based phrase distribution graph

However, involving human intervention, the qualitative analysis can be considered more subjective or intuitive in comparison to the other steps. Four trend lines (constant, emerging, fading, solidifying) are selected as the main characteristics of concepts. Further to the detection of content-dependent trend lines, characteristics of each phrase were examined and listed. In the fourth step, Chang and Blei (2009)'s relational topic models were utilized, however different than their model, the mapping process was made manually for the selected phrases (Figure 5).

The initial results show that there might be an accumulation in the usage of specific keywords. This information is not enough to explain certain tendencies and popularization of the concepts; however, frequency mapping still provides insights into the emergence and evolution of the concepts. The limited analysis of the selected keywords provided insights on the existence, usage, and transformation of the concepts in different domains. In this process, Turk and Cerovšek (2003)'s topic mapping technique which was used for extracting 2-word phrases were used and further it was adapted via a subjective selection of the authors. Different than the topic mapping technique, apart from the most frequent terms also some terms which are less frequent but might be influential in long terms were kept.

FINDINGS AND OUTCOMES

While the first column of Figure 6 includes the list of keywords refined by Martens and Turk (2003), the second column involves the keywords suggested by Celani and Veloso (2015). It is observed that the frequency of the three-fold specified phrases introduced by Martens and Turk (2003) such as "case based reasoning", "computer integrated construction", "Object Oriented Modeling" in IJAC database is quite low. On the other hand, more generic keywords suggested by Celani and Veloso (2015) took higher frequency scores. Further to machine-assisted word extraction of IJAC database, 60 keywords are selected and listed in the third column of Figure 6. In this step, as it is shown in Figure 2, the overlapping keywords among the first three columns of Figure 6 are merged. As a result of analyses based on 439 articles abstracts published in a 16 years period. During the initial data analysis, four prominent characteristics were observed:

- **Constant concepts:** Conveying the same meaning with minimum contextual change or without any change.
- **Emerging concepts:** It is related to how a

concept has begun to become a field-specific term by time with an increasing acceleration in trend curve and with an increasing ability to derive new phrases. The parameters for this item are the year-based frequency, the frequency-based trend curves and the ability to derive new phases. The ability to derive new phrases is represented with the radius of the circles in Figure 7.

- **Fading concepts:** According to year-based frequency, the concepts which become less popular by time. The concepts which have a decreasing frequency-based trend curve.
- **Solidifying concepts:** It refers to the group of words which are transformed into field-specific phrases by time. However, different than "emerging concepts", the keywords stay the same without becoming a part of new phrases. In other words, solidifying concepts do not manifest the ability to derive new phrases.

Figure 7 contains the information of selected keywords, count of repetitions, derivation of phrases, seen years, and characteristics of concepts. In Figure 7a, if we take 2003-2018 scale into consideration, the line of the best fit of the keyword "collaborative/collaboration" indicates a "fading" characteristics. However, the keyword "collaborative/collaboration" (C) and "collaborative design" (CD) have been a part of various phrases such as CD experience, CD simulation game, C Project, Distributed C Architectural Virtual Environments, interactive CD pedagogies, C AR, Distributed CD, voxel-based C modelling, CD research, C metadata management, C networks, C Semantic Management, 3D C environment, CD management, CD processing, C environment, Cyber-Enabled CD Studio, digitally mediated C studio, Network-centric CD platform, C architectural design, CD environment, CD practice, C development, C robotics, C digital design experience. In that sense, "collaborative/collaboration" keyword performs a "derivative" property and the ability to derive new phrase has a stabilization at an extent. Therefore, the derivative property of "collaborative/-collaboration" keyword is considered as "constant".

In Figure 7b, the year-based distribution graph of the keyword "learning" is shown. For the key-

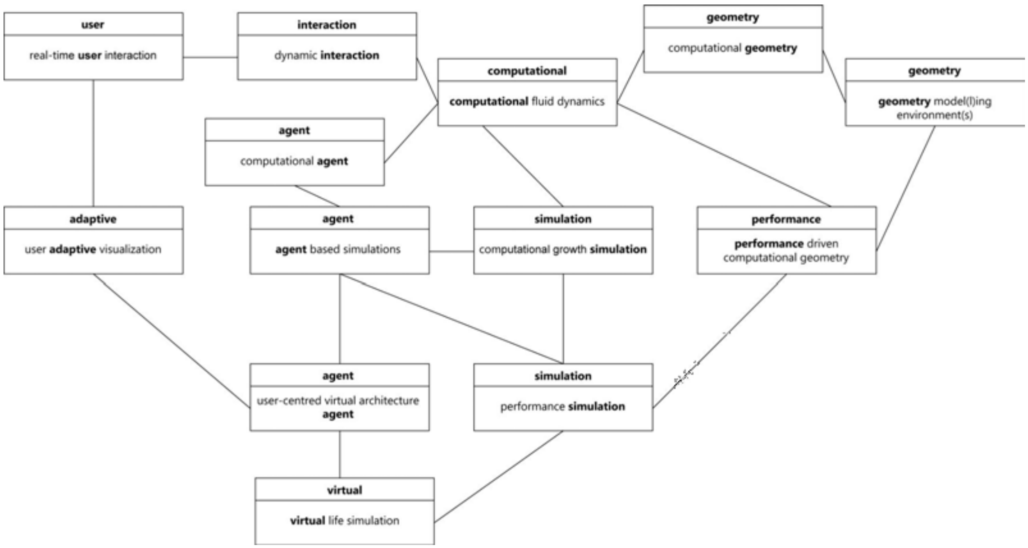


Figure 5
Relational topic model based on the selected keywords and phrases

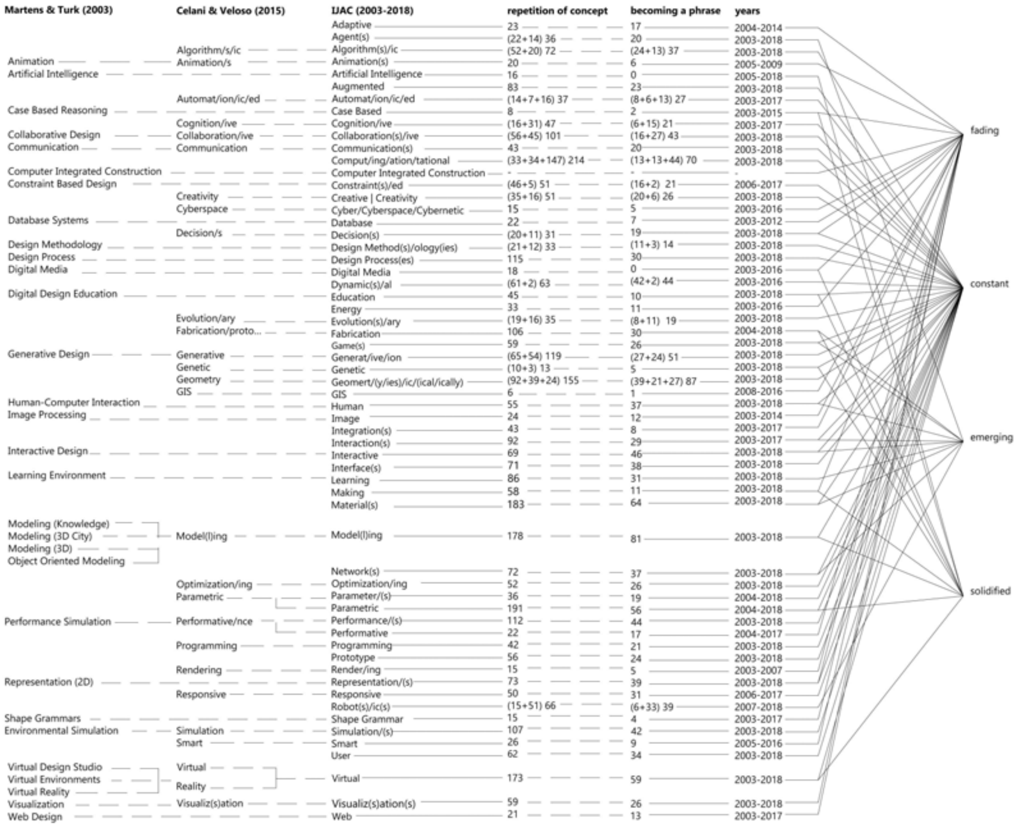
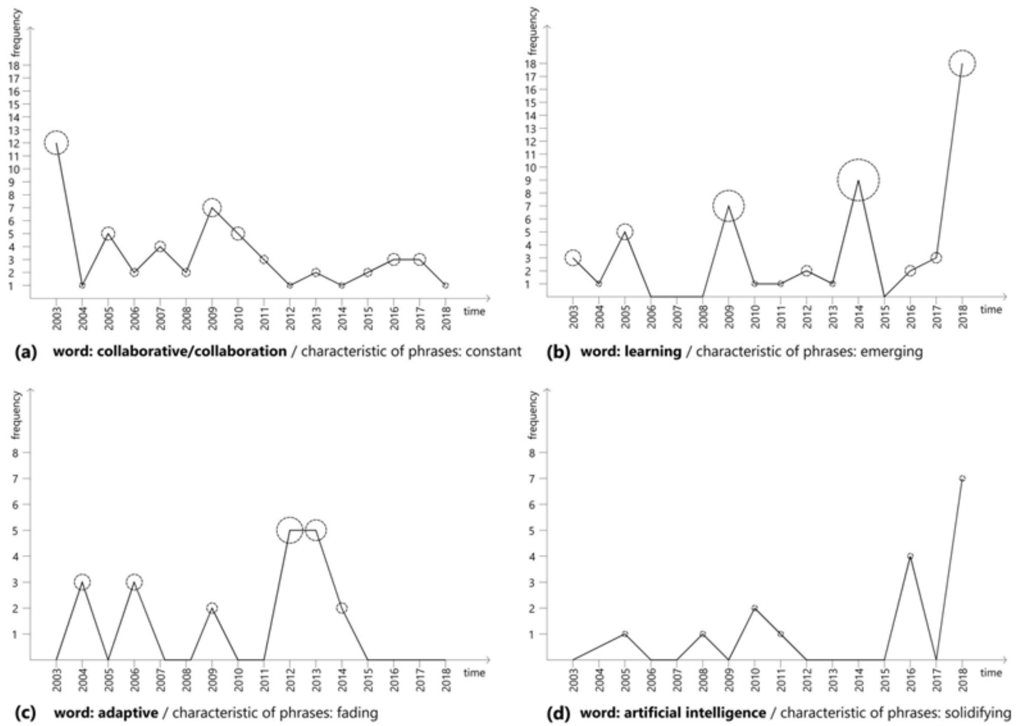


Figure 6
Comparative list of keywords and their features

Figure 7
Samples of four main characteristics.



word “learning”, the ability to derive new phrases has been distinctively higher in the years 2009, 2014 and 2018. The context, meaning and related concepts of “learning” differentiate dramatically such as “hands-on learning” (2003), “learning algorithms” (2004), “design learning” (2004) or Just-in-Place (JIP) learning (2014). On the other hand, “deep-learning” (2018), “deep learning algorithms” (2018), “function-driven deep learning” (2018) constitute a “new” topic node which displays an “emerging” characteristics.

The keyword “adaptive” is shown in Figure 7c which reveals the popularity of the keyword continues until 2014 discreetly. There have been pick years as listed: Adaptive information, Adaptive vision, User adaptive visualization (2004); Adaptive architecture/s, Adaptive assemblies, Complex-adaptive framework (2006); Real-time adaptive building skin systems, Real-time adaptive intelligent building skin systems (2009); Adaptive artificial lighting element, Adaptive design, Adaptive distributed robotics, Adaptive solar envelope (ASE) (2012); Adaptive hybrid structure, Adaptive mechanisms, Adaptive structure (2013); Adaptive liquid lens, Adaptive natural light spotlights (2014). The adaptive keyword is considered as a “fading” phrase, which at the same time it has been consisting of more complex phrases (engaging with more specific context) between 2012-2014.

Another example, the frequency-year graph of “artificial intelligence” is shown in Figure 7d. Having a solidifying characteristic, the term has been used as it is between 2003 and 2018. In other words, the number of the keyword seen increased however it does not carry a derivative characteristic.

DISCUSSION

As words and phrases with solidifying characteristics have become part of the design discipline, they cannot be ignored in digital design education. According to the findings of the study, it is observed that the words and phrases which have solidifying characteristics are used as tools or methods in architectural practice and education. The teaching and use of these tools and methods might be suitable for use in undergraduate education as they become understandable with the help of studies at a certain level.

The outcomes of this study might contribute to tracking the evolution of concepts their emergence or disuse in different time and contexts, and interrelations between different concepts. It is planned to extend the data source analysed in future studies in order to gain more consistent results. Despite the limitations of the outcomes of the study, it is still possible to speculate on the following issues. However, it should be kept in mind that an investigation of a larger amount of data might affect the results.

The trend curve of the "emerging" keywords displays an exponential growth and emerging keywords do not have a direct connection with the "tools". Being closer to the methods and approaches, the "emerging" keywords have the potential to reflect onto and transform the architectural curricula in the longer term. Due to its floating ground of meaning, it is thought that emerging keywords might be more influential in the graduate levels in the short term.

Another interesting finding is that the same keywords might convey more than one characteristic when we consider different timespans. Therefore, the scope, timespan, amount of source content are crucial indicators of the analysis process. This study can be considered relatively closer to the symbolic methods of language theories; however, in future studies, it is planned to elaborate the study through using stochastic Bayesian analysis methods. The selected 60 keywords will be used for further analysis based on four assumed elaborate the discussions on the reflection of tools, medium, techniques into the architectural design domain, and the existing concepts which gain new meanings.

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Digital Technologies in Latin American Architecture

A Literature Review from the Third to the Fourth Industrial Revolution

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This paper approaches the literature that combines the fields of Architectural Computing and Architecture and Urbanism produced in Latin America during the first two decades of the 21st Century. The main objective is to map the advancement of Digital Technology in Architecture and Urbanism in the context of the Third Industrial Revolution, in order to identify perspectives towards a Fourth Industrial Revolution. As methodology was applied a chronological survey of the literature produced in book format, predominantly printed in the 21st Century by Latin Americans researches in leading digital themes. At last, it can be verified that the production is still very scarce and still has not incorporated, in a significant way, the themes related to the Fourth Industrial Revolution.

Keywords: *Latin America, Digital Technologies, Industrial Revolution, Literature Review, Architectural Computing*

INTRODUCTION

In the history of Architecture, the topics on emerging digital technologies have been transversal to Economy, Society, Industry, where construction and architecture computing are not the exception. Schwab (2015) argues that the Fourth Industrial Revolution has its origin in the automation of production through electronics and informational technology and is not an extension of the Third Industrial Revolution, but a result of three reasons: velocity, scope, and system impact.

To analyze the evolution of the Third to the Fourth Industrial Revolution in Latin American Architecture, a thematic literature review about digital and emergent technologies was carried out. In this research, the bibliography considered was the one developed in the geographic territory where SIGraDi has been present during the first two decades of the 21st Century.

It is expected that this research contributes to the thematic of History and Future of CAAD, mapping the academic bibliographic field that discusses the issue of the implementation of Architectural Computing in the field of Architecture and Urbanism, identifying topics that may be linked to a Fourth Industrial Revolution in Latin America in the future.

As known, the bibliography published in book format in Latin American territory is very modest when compared to the amount of North American and European books. There are several factors that

Figure 1
Location of SIGraDi Conferences, 1997-2018

contribute to this, among which it can be supposed the bureaucratic difficulties, the high costs and the scarce resources assigned to books production, as well as the framing of an internationally incipient and little influential (academic) editorial market, and, therefore, not so profitable. Added to these problems is the lack of funding for long-term studies that generate results earning to be published as books.

It is also added the current stimulus and valorization to academic publishing in the form of papers in scientific journals, preferably distributed over the Internet in free access systems. In fact, another problem faced by the publishing of books refers to their distribution, which is also expensive. High investments are necessary so the books get to the book store's shelves to be purchased by readers. Therefore, when all of the difficulties of producing books have been surpassed, the problem of low circulation of the piece is faced, although the propagation over the Internet is also an alternative.

Given all these issues, it should be considered that the research presented in this paper is not exhaustive, but it proposes to bring to light some of the main publications and their authors. The effort to make a literature review reveals evidence of the ways of thinking from each period of time, consolidating the developed intellectual production and laying the basis for future connections.

The SIGraDi Conferences (since 1997), as well as the eCAADe (since 1983), disclosed papers that present thematic analysis based on bibliography. Therefore, this paper justifies itself by the importance of reviewing only published books, in order to provide a new panorama that includes some of the topics related to those recommended by Industry 4.0.

It should be noted that the history of publications by members of SIGraDi has had a very close relationship with eCAADe, in part due to the friendships of its founding members, such as Arturo Montagú and Thomas Maver. Thus, in the year of 2001, SIGraDi presented at the 19th eCAADe the history of its region (Montagú et al. 2001) where different authors reviewed the scenario of their countries. The experiences developed coincided with the first eCAADe round table led by Earl Mark, Bob Martens and Rivka Oxman (2001). Yet, in 2019, when SIGraDi and eCAADe hold their conferences together, actualizing collaboration and exchange of experiences between the two fellow societies, we present a review of the books published in Latin America.

Towards the end of the 20th Century, at the 17th eCAADe, Mark Clayton and Guillermo de Velasco (1999) presented a review of texts, which highlights the intense presence of Computer Programming. This review allowed the identification of 12 new topics in architectural computing education. Some years later, on the 20th eCAADe, Regiane Pupo and Gabriela Celani published *Trends in Graduate Research on IT & Architecture: A Qualitative Comparison of Tendencies in Brazil and abroad*. With 19 themes, they compared the trend of topics in digital technologies in Master thesis and PhD dissertations from Brazil and other countries between 1999 and 2006. Comparing it with the work of Clayton and Vásquez de Velasco, both coincide with the little production of Programming, Algorithms and Math Models topics.

In recent years, it has been seen the mapping of topics and conferences papers related to Computing Architecture, such as the work of Tassia de Vasconcelos and David Sperling which analyzes the teaching strategies supported by architectural digital techniques and produced by the Latin American community between 2010 and 2015 (Vasconcelos and Sperling 2016). Months later they set a retrospective from 2006 to 2015 (Vasconcelos and Sperling 2017) considering a systematic review of CumInCad database.

Thus, it can be verified that one of the main contributions of the literature review is the establishment of panoramas, which can provide the comprehension of the ways of thinking that have been consolidated over time. Therefore, the main objective of this paper is to evidence the panorama of the books published in Latin America in the almost twenty years of our century, pointing out their main topics.

MATERIALS AND METHODS

Our analysis takes as its starting point the work of Clayton and Vásquez de Velasco (1999) which seeks to answer the question from educators in Architectural Computing: "What do we need to teach our students now to be ready for this future?", in order to identify "the topics that we have taught in the past can help to identify those that should be continued and those that should be abandoned to make way for new topics". Likewise, this research seeks to recognize the topics proposed by the authors in the reference set.

Clayton and Vásquez de Velasco proposed 16 topics in the Architectural Computing education: *Design methods, Knowledge systems, Computing theory, Future (speculation on future systems), CAAD Theory, Computer literacy, Business applications, Programming, General computer graphics, CAD management and practice, 2D modeling applications, 3D modeling applications, Hypermedia, Animation, Communications, World Wide Web*. In their projections they have proposed five trends: *Distributed computing and electronic commerce, Convergence of telecommunications and computing, Real-time navigation through spatial simulations* and, finally, *Time-scaled animation phe-*

nomena that we have also included in our analysis list.

In addition, for the analysis of the books, it was included a list of trends associated to the Fourth Industrial Revolution, that were not identified in previous researches for this sort of analysis: *BIM, Robotics, Personal fabrication, Additive manufacturing, Big Data, Cloud computing, Blockchain, Nanotechnology and Internet of Things*.

This way, this work is the result of a qualitative research, based mostly in a literature review. At first, the CumInCAD database was sought in an effort to bring up papers that came up with a wider review of the Latin American bibliography production. It was found that there were a thesis survey (Pupo and Celani 2007) and a database of scientific papers (Vasconcelos and Sperling 2016, 2017), however, the book-based analysis had not been previously addressed, as proposed in this study.

Then, a literature review was made within books published by professors and researchers working in the field of Architecture and Urbanism in the countries covered by SIGraDI. Therefore, the books found were taken as an empirical object.

To select the books, a search was made among the papers published at the Conferences of SIGraDi since 2001. The collected data was complemented by searches over the Google Books database. Therefore, the period from 2001 to the present time is taken as the time frame of the study.

As a total, as shown in Table 1, 33 references were selected among books (22, marked in black) and catalogs (11, marked in white), in chronological order between 2002 and 2018, representing 5 countries: Argentina (10), Brazil (16), Chile (3), Colombia (1) and Mexico (1) and Uruguay (1). Spain (Álvarez and González 2017) is represented by two workshops held by the Architectural Association in Havana (Cuba, 2012) and Valparaíso (Chile, 2011). From there, after its reading and analysis, not only it brings up to the panorama understanding of the Latin American publishing developed over the last 20 years, but also it turns able to identify the authors and the themes pushed by them, as well as the countries that historically developed these initiatives and make them sustainable.

It is worth mentioning that, in this paper, we do not contemplate Proceedings, although they constitute a bibliographical material of extreme relevance, such as the Proceedings of SIGraDi Conferences, whose works can be accessed both by SIGraDi website [1], as well as directly by the CumInCAD database website [2], or, still, by Blucher Proceedings platform [3]. We have neither included in our literature review dissertations, thesis or research reports, not even scientific magazines or journals. At last, books that present a purely theoretical approach were also excluded, being directed to the teaching of certain software, for example, some titles of the brazilian publisher ProBooks, or manuals of a more pragmatic nature, such as the book published in 2015, in Peru, by Umberto Roncoroni, entitled as *Manual de diseño generativo*.

We privileged only the books approaching themes related to digital technologies predominantly linked to the universe of Architecture and Urbanism. Thus, the books focusing on the field of Communication were out of this study scope, such as books of Lucrécia D'Alessio Ferrara (*Cidade, entre mediações e interações*, 2016) and Lucia Santaella (*A ecologia pluralista da comunicação: conectividade, mobilidade e ubiquidade*, 2010), both brazilian, and also the books organized, in Brazil, by André Lemos (*Cibercidade: as cidades na cibercultura*, 2004; *Cibercidade II: Ciberurbe. A cidade na sociedade da Informação*, 2005; *Cidade Digital: portais, inclusão e redes no Brasil*, 2007).

Also not included were the books linked more specifically to the universe of Arts and Design, such as the book organized by Artur Matuck and Jorge Luiz Antonio, in 2008 (*Artemídia e cultura digital*), *Desorientação e colaboração no cotidiano digital*, organized in 2014 by Rejane Spitz, brazilian, and *Design: do virtual ao digital*, published in 2002, by Álvaro Guillermo Guardia Souto, or thoughts on the impact of the informatics on culture, such as Alejandro Piscitelli (*Ciberculturas*, 1995, and *Ciberculturas 2.0: en la Era*

Table 1
Computing Architecture books published between 2002 and 2018

Year	Authors	Country	Type of reference
2002	Duarte	Brasil	Book
2003	Celani	Brasil	Book
2003	Combes	Argentina	Book
2004	Montagú et al.	Argentina	Book
2004	Rodríguez	Argentina	Book
2004	Parra et al.	Chile	Book
2005	Piazzalunga	Brasil	Book
2006	Prestes	Brasil	Book
2006	Rodríguez	Argentina	Book
2007	Rodríguez	Argentina	Book
2007	R. García	Chile	Book
2008	Astudillo et al.	Chile	Book
2009	Patiño & Arbeláez	Colombia	Book
2010	Da Silva	Brasil	Book
2010	Muñoz	Argentina	Catalog
2011	Kowaltowski	Brasil	Book
2011	Muñoz	Argentina	Catalog
2012	Arantes	Brasil	Book
2013	Rodríguez et al.	Argentina	Book
2013	Scheer et al.	Brasil	Book
2013	Muñoz	Argentina	Catalog
2013	Celani	Brasil	Catalog
2013	NOMADS	Brasil	Catalog
2014	F. García	Uruguay	Catalog
2015	Sperling et al.	Brasil	Catalog
2016	Braida et al.	Brasil	Book
2016	Muñoz	Argentina	Catalog
2016	Alvarez et al.	España	Catalog
2017	Cordeiro & Costa	Brasil	Book
2018	Celani	Brasil	Book
2018	Belmiro	Brasil	Book
2018	Schereen et al.	Brasil	Catalog
2018	Anzalone et al.	México	Catalog

Type of reference ■ Book □ Catalog

de las máquinas inteligentes, 2009), and *As teorias da cibercultura: perspectivas, questões e autores* (Rüdiger 2013). Texts of a predominantly philosophical nature were also not included, such as the book by Umberto Roncoroni, peruvian, *Filosofía y software: la cultura digital detrás de la pantalla* (2012).

RESULTS AND DISCUSSION

Background: Books from the end of the 20th Century

It is emphasized that, unlike the constant bibliographical production of the Northern Hemisphere, Latin America had little specialized production on book format. However, SIGraDi, since its foundation, has brought authors together, creating milestones on the situation of the region.

Adapted from Clayton and Vásquez de Velasco (1999:154), Table 2 shows in black the relation between the distinct topics regarding the computing architecture and the bibliographical production between 1975 and 2000. The Table 2. was adapted to relate it to the only Latin American books published in the 1990s. This decade precedes our research and points out 5 books published in two of the twenty countries that compose Latin America: Argentina (2) and Brazil (3). Unlike the Northern Hemisphere, this production meant, for Latin America, self-managed efforts promoted by public universities, in research spaces such as the *Laboratorio de Técnicas Avanzadas en Diseño*, in Venezuela, (created in 1974), which organized the first venezuelan conference about the application of computers in architecture (1999). Another references are the School of Architecture and Urbanism of University of São Paulo, which organized the International Seminar: *Computacão: Arquitetura e Urbanismo* (Dantas, 1992), and the *Centro de Creación Asistido por Ordenador* (CAO) in Argentina (created in 1989) which was organized in 1997 the *1° Seminario de la Sociedad Iberoamericana de Gráfica Digital* (SIGraDi) in the School of Architecture, Design and Urbanism of the University of Buenos Aires.

Arturo Montagú was the main impeller of the foundation of SIGraDI. He also was very influent and left a great legacy. Some of his published works, at the late 20th Century, are *Aporte de la Informática en la Arquitectura, el Diseño y el Urbanismo* (in 1993, in partnership with Mario Nariño and María Igarabal) and *DatArq 2000 base de datos de la arquitectura moderna y contemporánea* (1999). Also in 1999, in Brazil, Fábio Duarte published a short book entitled *Arquitetura e Tecnologias de Informação: da Revolução Industrial à Revolução Digital*. In this book, Fábio Duarte, within a historical perspective and with references to projects of several architects, approached some topics related to electronic and digital architecture, among which are issues about models and simulations, immersion in virtual environments and de-

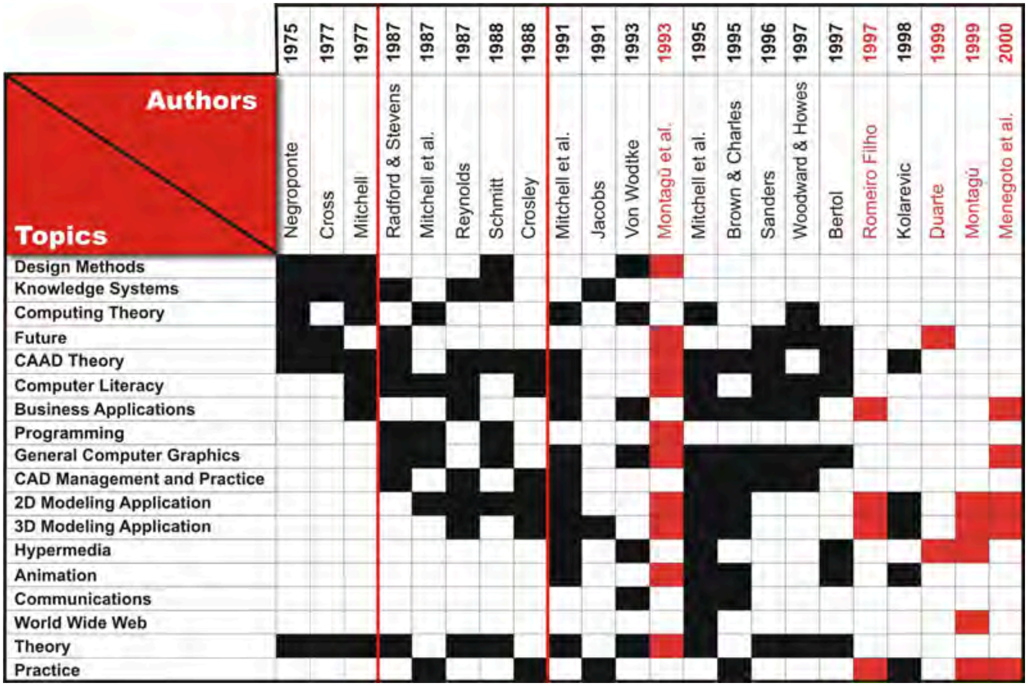

Table 2
Computing Architecture references between 1975 and 2000

materialization. And, in 2000, Jose Luis Menegotto and Tereza Cristina Malveira de Araujo published the book *O Desenho Digital: Técnica e Arte*.

These books, published near to the transition from the 20th Century to the 21st, might be considered pioneers in Latin America, especially since they brought the first regional approaches to the incorporation of digital technologies in the scope of Architecture and Urbanism, even presenting books published outside the Latin American geographical space to a larger audience.

Figure 2
Cloud of words from books titles raised in research

21st century: Computing Architecture books in Latin America

In 2002, Fábio Duarte presented as another contribution the book entitled *Crise das matrizes espaciais*, in which he explored, among other themes, the multimedia city, the technological culture and cyberspace, the trans architecture of Marcos Novak, the fluid architecture of Nox and the hybrid spaces. In 2003, in Argentina, Leonardo Combes was the editor of the book *Contribuciones a los sistemas de diseño*. In Brazil, on that same year, Gabriela Celani published the book *CAD Criativo*, as a result of "a series of CAD educational experiments held in different architecture and engineering programs" (Celani 2003, p. XIV, translated by the authors).

In 2004, Montagú, Pimentel and Groisman published *Cultura Digital: comunicación y sociedad* with prologue by Thomas Maver, presenting the societies' role with a regional view of how technology was applied in architecture and design. In Argentina, Diana Rodríguez published *Hipermedios y modelos virtuales de fragmentos urbanos* and, in Chile, Juan Parra, Rodrigo García and Iván Santelices published the second edition of *Introducción Práctica a la Realidad Virtual*. In 2005, Renata Piazzalunga, brazilian, published *A virtualização da arquitetura* problematizing the reflections of the virtual in architecture, in its processes of perception and representation.

In 2006, Diana Rodriguez Barros from the Editorial Board from SIGraD published *Experiencia digital: Usos, prácticas y estrategias en talleres de arquitectura y diseño en entornos virtuales*. It concerns of a text with critic reviews of 37 co-authors and regional cases. In Brazil, was also published the book *Cidade digital: infoinclusão social e tecnologia em rede*, by Evandro Prestes Guerreiro. On that same year, a thematic project was started with the permission for Gabriela Celani to translate the book *The Logic of Architecture* (in 2008, look for Mitchell, 2008) and it finished with the publishing of *O processo de projeto em arquitetura: da teoria à tecnologia* (Kowaltowski et al. 2011).

In 2007, Diana Rodriguez, once more presented another contribution by editing the book *URBAMEDIA: base de datos urbanos de áreas centrales, casos de ciudades argentinas y latinoamericanas*, while Rodrigo García, chilean, published *Animaciones Arquitectónicas*. In 2008, in Chile, Claudio Astudillo and Mariapaz Velázques (editors) published *Propagaciones. Exploración de nuevos escenarios y campos de investigación tecnológica*.

In the following year, in 2009, Ever Patiño and Elsie Arbeláez published, in Colombia, *Generación y transformación de la forma: Morfología, geometría, naturaleza y experimentación*. The book *Urbanismo paramétrico: parametrizando urbanidade*, by Robson Canuto da Silva, brazilian, was launched in 2010, presenting a reflection and practical applications of parameterization in urbanism and spatial syntax. In 2012, Pedro Fiori Arantes, in Brazil, published *Arquitetura na era digital-financeira: desenho, canteiro e renda da forma*, which focus on issues on subjectivity and experience in postmodern architecture, electronic drawing board and hybrid construction site.

In 2013, once more on behalf of SIGraDi, the Editorial Committee published *Didáctica Proyectual y Entornos Digitales: prácticas y reflexiones en escuelas Latinoamericanas de Arquitectura y Diseño*. It's a book organized by Diana Rodriguez, Maria Tosello and David Sperling, which is composed of texts written by 51 co-authors and is divided in three sections that gathers experiences of five countries of the region (Argentina, Brazil, Chile, Perú and Venezuela). On this same year, Scheer et al. (2013) in Brazil, published *Modelagem da informação da construção: uma experiência brasileira em BIM*.

In 2016 the book *101 Conceitos de Arquitetura e Urbanismo na Era Digital* was published, edited by Frederico Braida et al. (2016), with a prologue by Gabriela Celani, which brought together 46 co-authors working in Brazil and Portugal with the aim of presenting some of the most relevant words and concepts of the contemporary universe of digital architecture. Aristóteles Lobo de Magalhães Cordeiro and Germana Costa Rocha organized, in 2017, in Brazil, the book *Modelos em arquitetura: concepção e documentação*.

In 2018 the book *Arquitetura contemporânea e automação: prática e reflexão* was launched, edited by Gabriela Celani and Maycon Sedrez, emphasizing aspects such as digital manufacturing, generative systems and evolutionary algorithms. The book brings texts from 13 authors and 14 interviewees exponents with of digital architecture in Brazil and abroad.

In addition to these books that bring a more consistent theoretical discussion, there are also some booklets published in a more independent way by research laboratories, such as the books by Muñoz (2010, 2011, 2013 and 2016), Celani (2013), *NOMADS - Núcleo de Estudos de Habitares Híbridos* (2013) and Passaro et al. (2017). These books and exhibition catalogs, also contribute to the establishment of the reflection panorama on the topics present in Latin

American scenario of computing architecture.

Among the exhibition catalogs, the Homo Faber exhibitions stand out. In 2015, Latin America was for the first time the headquarters of CAAD Futures and, on that occasion, the catalog *Homo Faber: Digital Fabrication in Latin America* (Sperling and Herrera 2015), which was a result from the exhibition that sought to map the development of Fab Labs in Latin America. Participating in the exhibition were 24 Fab Labs from Argentina, Colombia, Brasil, Chile, Uruguay and Perú. In 2018, on the occasion of the XXII SIGraDi Conference, it was published the catalog *Homo Faber 2.0: Politics of Digital in Latin America*, edited by Scheeren, Herrera and Sperling, gathering 37 projects from Mexico, Costa Rica, El Salvador, Colombia, Perú, Brazil, Chile, Argentina and Uruguay. On the same year, within the context of ACADIA 2018, the catalog of the exhibition *Digital Craft in Semi-peripheral Nations*, (Anzalone et al. 2018), was published based on three criteria: Material Systems, Labor Culture and Socio-political opportunities in order to explore the exchange between the technology of the digital and the artisan of the handmade, with projects from Brazil, México, Guatemala and Argentina.

In Table 3, the books are listed next to the topics used in this study. As it can be noticed, there is a greater concentration of publications that approach the *personal fabrication* (15), with a significant recurrence after 2011, while the Fourth Industrial Revolution's themes themselves have not reached the publications in the form of a book yet. Concerning the words present in the titles, those are highlighted by the occurrence: *digital* [digital] (9), *arquitetura* [architecture] (8), *diseño* [design] (6), *arquitectura* [architecture] (5) e *urbanismo* [urbanism] (3). Figure 2 shows

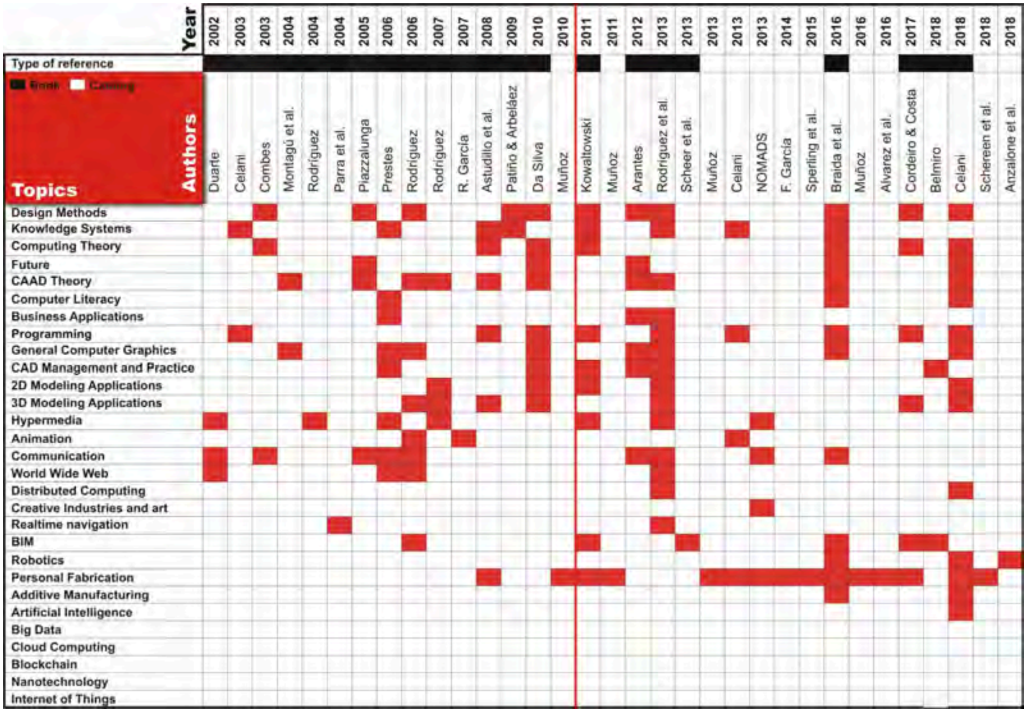

Table 3
Computing Architecture in Latin America books in the 21st century

the word cloud of the titles in their respective languages, excluding prepositions and articles.

As it can be verified, although the publication of books about this thematic is scarce in Latin America, the big picture analyzed reveals the context in which the discussion on digital technologies in the field of Architecture has taken place in this region. It also might be underlined that, from a bibliographical references analysis, the Latin American authors are in permanent dialogue with the North American and European bibliography, from which they manage to introduce their countries in the discussions carried out in the digital and globalized world scenario, strongly influenced by the Fourth Industrial Revolution.

FINAL CONSIDERATIONS

As it was shown, this paper enlightens the Latin American intellectual production recorded in the books published in the first years of this new millennium, revealing authors and ways of thinking in Architecture influenced by digital technologies.

The 37th eCAADe and the XXIII SIGraDi Conference coincide in a congress around the Architecture in the Age of the Fourth Industrial Revolution, as a context that reflects the future of technology in the education and practice of Architecture. Therefore, it becomes pertinent and timely, once again as it was in 1999, to review the bibliographic production developed in the first two decades of the 21st Century, in order to map the academic discussions on digital technologies carried out in Latin America .

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Matter - ADDITIVE MANUFACTURING

Re-perceive 3D printing with Artificial Intelligence

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How can machine learning be combined with intelligent construction, material testing and other related topics to develop a new method of fabrication? This paper presents a set of experiments on the dynamic control of the heat deflection of thermoplastics in searching for a new 3D printing method with the dynamic behaviour of PLA and with a comprehensive workflow utilizing mechanic automation, computer vision, and artificial intelligence. Additionally, this paper will discuss in-depth the performance of different types of neural networks used in the research and conclude with solid data on the potential connection between the structure of neural networks and the dynamic, complex material performance we are attempting to capture.

Keywords: *3D printing, AI, automation, material, fabrication*

1. BACKGROUND

After years of extensive development, artificial intelligence has proven its potential to achieve human-level performance in many areas such as image recognition, speech recognition, and decision-making. This technology can be used in a far broader direction than the abovementioned fields. Currently, various fields are exploring how to use artificial intelligence technology to solve professional problems. In the field of intelligent construction, architects continually explore material understanding and construction methods.

In the field of digital construction, the application of digital methods to traditional building workflows has always been one of the important research topics in the construction industry. The development of automation technology, especially the emergence of various machine manufacturing, has brought new possibilities for the construction industry. In material development and use, progress in digital fabrication has benefitted from incorporating dynamic material properties as generative and integrating design factors (Menges, 2012a). Architects and construction builders can gradually transfer materials to the digital manufacturing field. Numerous studies have been conducted to digitize craftsman's traditional work, ranging from utilizing digital fabrication tools to simulating the handiwork of handcrafted items (Brugnaro and Hanna, 2018) to augmenting actuators with sensors, to incorporate the real-time feedback on a material's state during the design production process (Mueller et al., 2012).

Contrary to the human understanding of material performance based on explicit material properties and behavioural models, neural networks are able to fit any function allotted enough training materials without human understanding of the logic behind it. Therefore, is it possible for us to unite artificial intelligence (AI) and mechanical automation processes to generate an end-to-end material performance model that bridges fabrication control and outcome of the form while utilizing complex and dynamic material behaviours without a scientific understanding of the material properties? We will offer the best possible exploration of this issue.

Recently, research has been conducted to use AI to develop a novel fabrication method. For example, neural networks (NNs) have been explored to develop design tools for doubly curved metal surfaces (Rossi and Nicholas, 2018), and in other cases, various robot woodcarving techniques have been assessed in response to material properties (Brugnaro and Hanna, 2018).

This research will potentially give architects and designers a universal method to access a diversity of material properties and enable designers to program material behaviour and achieve design intentions without systematic understandings of the mechanism behind material performance.

2. PREVIOUS RESEARCH

This research is a continuation of a previous method that utilized robotic automation and AI to observe the complexity of flexible elastomer materials in regard to their bending and deformation features(Luo, 2018). The experiment described in this paper is developed to seek more insight to the questions raised from previous studies: 1. Is this a universal method that manages material properties and has no established material model? 2. Instead of mapping material distribution/properties to material behaviour, can this process generate a more abstract end-to-end model that directly maps mechanical control of the fabrication tools to the behaviour of material and the final form? 3. How will this method impact common fabrication technologies?

3. OVERALL SYSTEM

In this research, we are applying the method of automatic generation of the material performance model with AI to one of the most common fabrication technologies-3D printing with PLA.

We have developed a system for a printer to print a line across two supports at either end and to let the material naturally drip into a curve. As a thermoplastic material printed in such an unsupported manner with alternating extrusions, movement speed determined by Gcode, and under the compound play of gravity and intermolecular forces, the PLA string will solidify into a curve with uneven curvature.

This system is different from the traditional additive layering printing system. Conventional printing systems require layer-by-layer printing from bottom to top, and additional brackets are required for some of the suspended areas. The system is capable of efficiently printing a 2.5D or 3D spatial wireframe without additional support. Owing to the complexity of intermolecular forces, unknown material properties, etc., planning and control of the printing path is impossible to achieve with current 3D printing software, as this 3D printing method relies on the dynamic heat deflation of PLA that has no established method for simulation or prediction. Confronting such a challenge, a machine learning approach is developed to build an end-to-end workflow. After collecting a large number of training samples with an automatic system and image processing, we created two models to learn the rules for this new printing method: One forward model calculates the printed curve via a given Gcode, and one backward model predicts the Gcode controlling the printer by producing the curve that the designer intended to print (Figure 1).

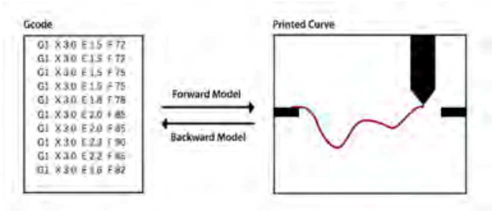
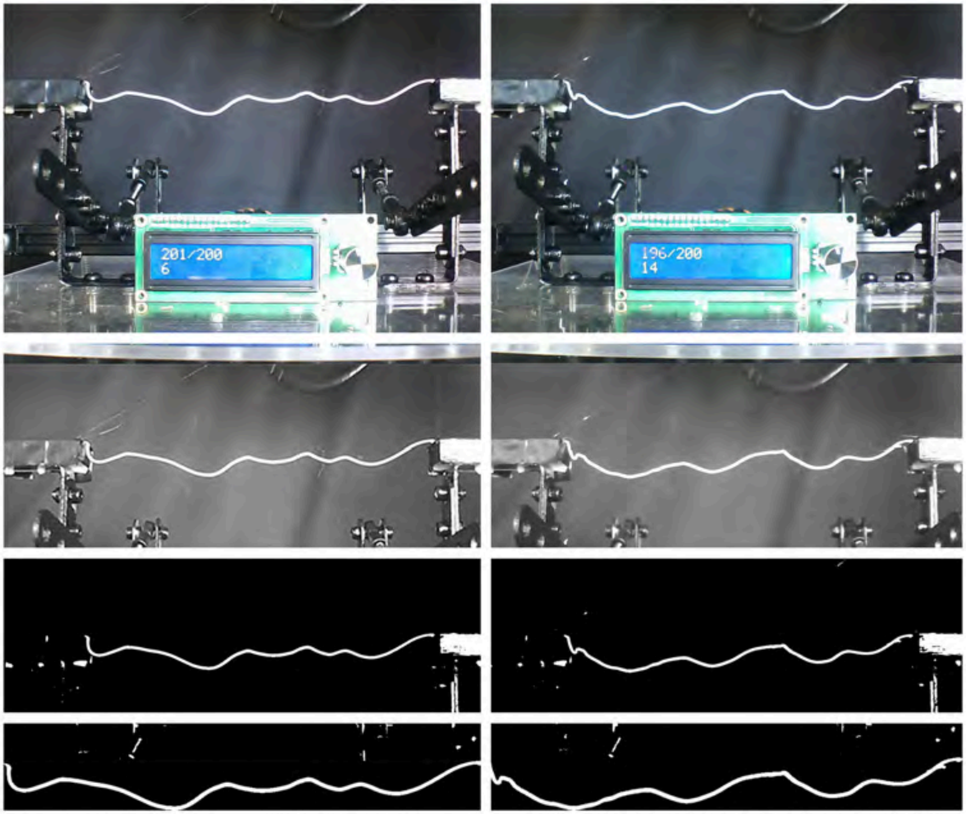


Figure 1
Two-way mapping between Gcode and the printed form

The main workflow of the method includes the following steps.

1.Development of an automatic mechanical system. The next step is processing the collected im-



	0	1	2	3	4	5	6	7	8	9	...	160	161	162	163	164	165	166	167	168	169
coordinate_x	0	5	11	16	22	27	33	38	44	49	...	886	891	897	902	908	913	919	924	930	935
coordinate_y	5	0	0	1	1	2	4	5	7	9	...	53	54	54	53	52	48	40	8	5	2

	0	1	2	3	4	5	6	7	8	9	...	160	161	162	163	164	165	166	167	168	169
coordinate_x	0	5	11	16	22	27	33	38	44	49	...	882	887	893	898	904	909	915	920	926	931
coordinate_y	2	0	0	1	2	3	5	7	11	14	...	39	37	36	37	45	34	13	5	2	2

Figure 2
Image to data

age, extracting the data describing the material performance with image recognition, matching the fabricated form with the Gcode that controls the movement of the extruder and formatting it for machine learning.

In the experimental design, we printed white PLA materials against a dark background for maximum contrast. In this way, we can easily extract the experimental objects and transform the pixel points into sequenced data according to the requirements of subsequent experiments with image processing by Python and Opencv. At the same time, the curve data generated from the image is matched with the corresponding printed Gcode, forming a complete training sample (Figure 2).

2.Training the forward and backward models. We use the deep neural network model in machine learning to build a model for predicting curves from Gcode and a model for predicting Gcode from curves, using appropriate data augmentation techniques. By selecting different types of models, different model structures and different hyperparameters for comparison, the best-performing models are finally trained for the subsequent experimental sessions. Information about neural networks and specific models will be detailed in the next section.

3.Model and method evaluation. The trained model was used to predict the Gcode from a given curve, which was printed and compared to the deviation between the predicted curve and the actual print to evaluate the ultimate effect of the method.

4. MODEL TRAINING

1. Deep learning

Traditional machine learning and signal processing techniques explore shallow learning structures that contain only a single layer of nonlinear transformation. A commonality of shallow models is that they contain only a single simple structure that converts the original input signal into a particular problem regarding a spatial feature. The concept of deep learning stems from the study of artificial neural networks, which combines low-level features to form more abstract high-level representations (attribute categories or features) to discover distributed feature representations of data. In 2006, Hinton proposed a deep neural network for complex general learning tasks in science, pointing out that networks with a large number of hidden layers have excellent feature-learning capabilities(Hinton, 2006;Yoshua 2009;Arel, 2010). Humans have found a way to deal with "abstract concepts" with the help of neural networks. The research of neural networks has entered a new era, and deep learning has begun to enter a period of rapid development.

In this paper, three models-neural networks (NNs), convolutional neural networks (CNNs) and long short-term memory (LSTM)-were tried in the experiment. By comparing and analysing the performance of the three models, the best performing model was selected and utilized in subsequent experiments. In choosing a loss function, we used mean square error (MSE) and mean absolute error (MAE) evaluation methods. The lower the values of MSE and MAE, the smaller the model error and the better the performance.

NN is the simplest deep learning model, and for some simpler problems, it is the most efficient solution.

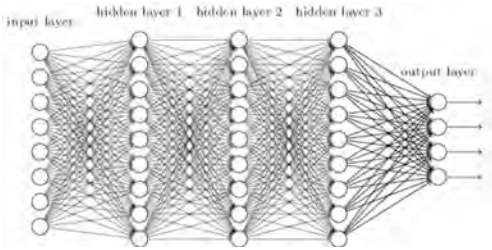


Figure 3
Structure of Neural Network (NN)

Convolutional neural networks are an important milestone in the development of deep learning. CNNs can significantly reduce the number of free parameters in the network. A small portion of the image referred to as the localized region in the CNN serves as the bottommost input to the hierarchical structure. Information is passed through different network layers, so each layer can acquire significant features of the observed data that are invariant to translation, scaling, and rotation (Erhan , 2010)(Figure 4).

A RNN has a cyclic network structure and the ability to maintain information. Its network structure is shown in Figure 5 The cyclic network module in the RNN transfers information from the upper layer of the network to the next layer. The output of the hidden layer of the network module depends on the information of the previous moment. The LSTM network is an extension of the RNN and is specifically designed to avoid long-term dependency issues. The LSTM's repetitive neural network module has a different structure, and unlike the plain RNN, there are four neural network layers that interact in a special way(S. Hochreiter, 1997).

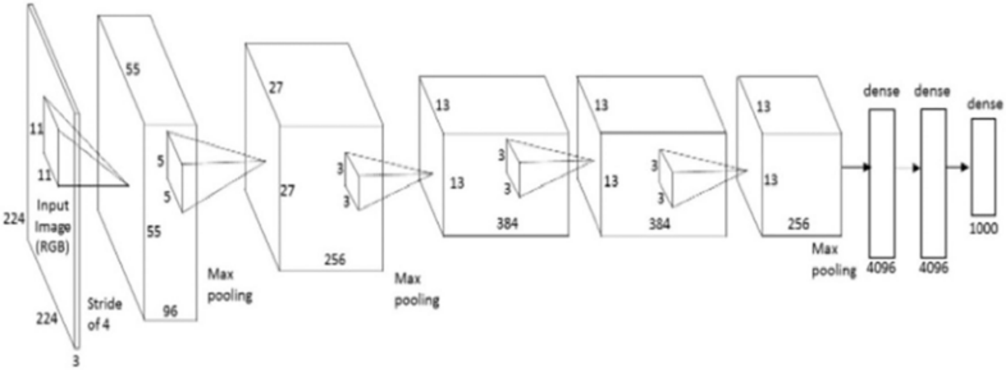


Figure 4
Structure of
Convolutional
Neural Networks
(CNN)

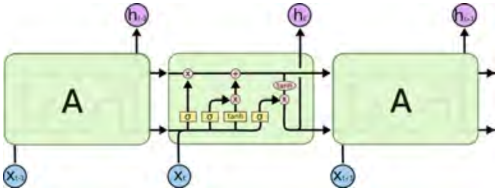


Figure 5
Structure of Long
Short-Term
Memory (LSTM)

2. Data augmentation

In machine learning, sometimes there are not enough training samples, or the sample distribution is not balanced, which may lead to poor training results and overfitting. To solve these problems, it is necessary to generate some new samples with data augmentation, on the premise of ensuring accuracy on the basis of existing samples, and expand the training per se. In the process of collecting samples, we used certain consistent characteristics of the printer and image processing to conduct data augmentation.

3. Forward model

For the three models-NN, CNN, and LSTM-the comparisons of different amounts of input data and different model structures are shown below.

For the three models, the overall performance of the LSTM model is significantly better than the NN and CNN models. For sample input data of different sizes, the greater the number of samples as a whole, the better the model performance; this reflects that the deep learning model has a strong dependence on the size of the training samples.

However, in the case of 1100 and 1600 training samples, the performance of the model has its advantages and disadvantages. In response to this phenomenon, we have conducted further research. We train all the samples in the training set, but for the test set, we divide it into subsets according to the different amplitudes of the curves and separately evaluate the prediction.

Figure 6
Performance of
forward models

It can be concluded from the above figure that the performance of models for different amplitude intervals is significantly different. For the three models, the amplitude is predicted most accurately in the 10-20 mm range, and the more deviation there is from this amplitude range, the worse the model becomes at prediction. In the amplitude range of 10-20 mm, the average prediction error of each coordinate is only approximately 2-3 mm, which indicates that the

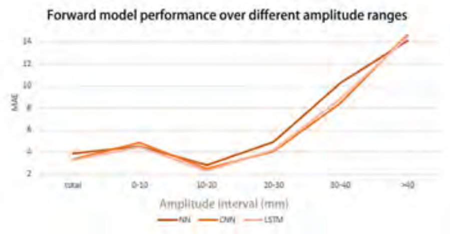


Figure 7
Forward model performance over different amplitude ranges

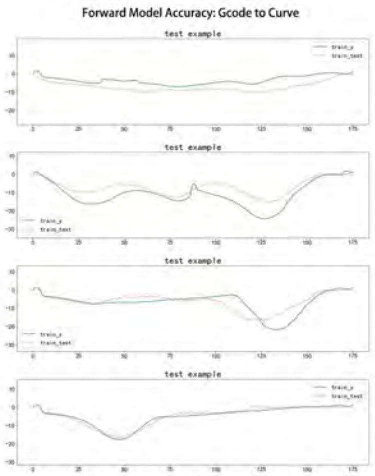


Figure 8
Forward Model Accuracy: Gcode to Curve

Figure 9
Performance of backward models

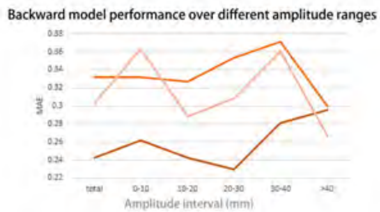


Figure 10
Backward model performance over difference amplitude ranges

method is very feasible. Selected testing samples are shown in Figure 8. One possible explanation is that in the process of collecting samples in the early stage, the distribution of the samples has a certain deviation. At a higher sample distribution with an amplitude closer to 10-20 mm, the prediction effect of the interval is obviously better than other intervals. A solution to this issue can be further improved upon in subsequent studies.

4. Backward model

In the previous experiment, we trained the model to predict the shape of the curve with a given Gcode. However, in practice, what is more commonly needed and has more practical value is a model that predicts a possible Gcode from a given targeted curve.

Similarly, for this backward model, we continued with the three models of NN, CNN, and LSTM, as well as different input sample data volumes and different model structures. The results are given below (Figure 9).

For the predicted Gcode model, the differences between the different models are not as large or even significantly different from those of the predicted curve model. However, as the number of input samples increases, the backward prediction accuracy of the CNN and LSTM decreases significantly more than the NN. This aspect shows that we are do not have enough samples to sufficiently train the backward model. On the other hand, it also shows that the NN is more adaptable to reverse prediction.

Similarly, we use a full sample to evaluate the performance of the inverse prediction model over different intervals (Figure 10). In the 20-30 mm range, the NN can still maintain a good level of accuracy compared to the CNN and LSTM. Therefore, the NN is more suitable overall for the reverse prediction model. Selected testing samples are shown in Figure 11.

Figure 11
Backward Model Accuracy: Curve to Gcode

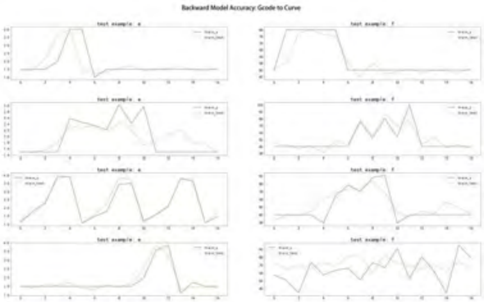
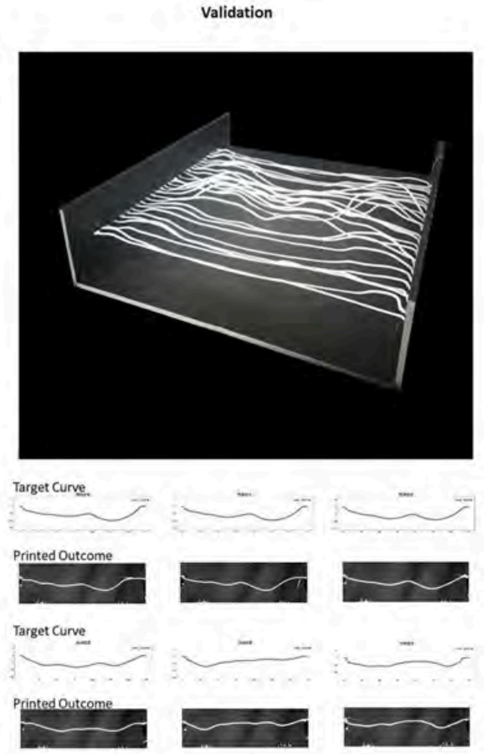


Figure 12
Validation and application in design



5. METHOD AND MODEL EVALUATION

Returning to the purpose of this research, we hope to propose a new manufacturing process based on dynamic material properties. In terms of the perceived material properties, our model has already achieved a positive result. For a given set of Gcode, printed shapes can be predicted with a certain degree of accuracy. Considering the actual production value, however, we still have to focus on whether we can predict a possible Gcode set for the curves intended for printing.

Therefore, we will conduct a set of experiments to validate the trained model. A simple landscape scheme is put together and divided into a set of cut-out curves. The trained model is used to predict the Gcode for printing. We print out the Gcode and compare the actual print results to the expected curves to evaluate the effects of the method and model.

The actual print results are basically consistent with the expected curves (Figure 12), which proves the feasibility of the method.

6. CONCLUSION

The conclusions of the paper can be summarized as follows: First, the method and outcome in this paper establishes a novel method for 3D printing of spatial wireframes and its development process with an automated machine learning process. Second, it has expanded and generalized the potential application of the proposed workflow beyond the limitation of current scientific material models. Third, such a method is capable of creating a direct end-to-end connection between the control of the fabrication process to the final form resulting from a complex form fining process, avoiding complicated interim steps and calculation. Last but not least, compared to the traditional method of developing material models that require different fields of knowledge and workflow for different material properties, the method and logic of the work described in this paper is universal and proven to be capable of generalization when applied to producing a diversity of material performance models that encompass multiple systems of non-related material behaviour, such as the active process of bending elastomer and the reform process of melting thermoplastics.

For architects, architectural design ultimately relies on the selection and construction of materials. In the long run, new building materials and new construction methods will bring about tremendous changes in the construction industry, as well as new architectural styles. We believe that the approach presented in this article will be a positive inspiration to herald this change.

7. ACKNOWLEDGMENTS

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Direct Digital Manufacturing of Architectural Models using Binder Jetting and Polyjet Modeling

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Today, architectural models are an important tool for illustrating drawn-on plans or computer-generated virtual models and making them understandable. In addition to the conventional methods for the manufacturing of physical models, a wide range of processes for Direct Digital Manufacturing (DDM) has spread rapidly in recent years. In order to facilitate the application of these new methods for architects, this contribution examines which technical and economic results are possible using 3D printed architectural models. Within a case study, it will be shown on the basis of a multi-storey detached house, which kind of data preparation is necessary. The DDM of architectural models will be demonstrated using two widespread techniques and the resulting costs will be compared.

Keywords: *Architeetual model, CAAD, Direct Digital Manufacturing, Binder Jetting, Polyjet Modelling*

INTRODUCTION

Architectural models have been an important architect's work and design tool for centuries to illustrate two-dimensional designs as 3D sculptural objects. Using design models, architects and builders can quickly understand and evaluate the cubature of a design as well as the spatial relationships. Especially for nonprofessionals, who are inexperienced in the reading of architectural drawings, a model is often more vivid than two-dimensional representations as sketches. In contrast to architectural representations as virtual reality, e.g. with the aid of large-scale screens (i. e. powerwall) or virtual glasses, the architectural model provides direct and haptic access to the design. It is advantageous that for viewing no time-consuming data preparation by rendering and no cost-intensive hardware (i. e. projector, VR glasses) is needed.

Architectural models can be manufactured using a number of conventional manufacturing techniques. Thus, various model parts are made of plastic metal, wood, glass, paper or even plaster. The manufacturing takes place indirectly with elaborate milling or cutting machines that are equipped with different tools and also need to be programmed. Subsequently, complex assembly work is usually necessary to connect the different model parts and materials . For some years, therefore, the methods of Additive Manufacturing (AM) or Direct Digital Manufacturing (DDM, shortly: 3D printing) have been used extensively in the production of architectural models. In addition to the direct manufacturing, these methods also offer the advantage that complex and curved freeform geometries can be implemented.

The basis for AM is always a 3D virtual model created using CAAD software. This model is then checked during data preparation for printability and redesigned considering particular design guidelines and restrictions. Subsequently, the 3D printing can be done. A major obstacle to the further spread of additive manufacturing is that many architects do not have the necessary knowledge for data processing. In addition, especially in small architect's offices still mainly 2D CAAD software is used, so that a 3D model for additive manufacturing is not available. As a result, the 3D models have to be extensively redesigned from the 2D designs (such as floor plans and façade plans). In this article it should therefore be analyzed how a 3D model can be transferred directly from the CAAD data to additive manufacturing.

Also for the additive manufacturing of the architectural models, a large number of methods are available today, e.g. models are made of plaster, plastic, metal or paper. In this contribution, two of the most important methods for the production of architectural models, namely Binder Jetting (BJ: printing material: gypsum-plastic powder with liquid adhesive) and the Polyjet Modeling (PJM: printing material: UV-light-curing photopolymer) are considered in more detail. This clarifies the technical and economic differences arising from the use of different 3D printing methods and materials.

LITERATURE REVIEW

The development of additive processes began more than 30 years ago with a patent for stereolithography. Since then, many different processes have been developed and put on the market. All methods have in common that the model are built layer by layer. Likewise, in all processes, the layers are built directly from the CAAD data without additional aids such as tools or clamping devices. The market research by Wohlers et al. (2017) show high growth rates for years both in the sale of 3D printers and in the number of additively produced models. For two decades, additive manufacturing has also been used to produce architectural models. Thus, the studies of Ryder et al. (2002) showed that the additive methods could be usefully used despite the high costs involved in the implementation of architectural models. However, according to Gibson et al. (2002) the 3D-printed model were still only limited usable due to the small available size and the defective appearance.

Since then, the technology has evolved significantly. As Wong and Hernadez (2012) show, today printers with a much larger space are available. In addition, today there are systems on the market that can produce both monochrome and polychrome models. According to Stavric et al. (2013) can architectural models thus be created by additive methods as well as by reverse engineering. Even partially transparent models can be created today. In order to find a suitable additive manufacturing process for architectural models, Mancanares et al. (2014) developed a catalog with important criteria. The benefits of digital manufacturing become particularly apparent when complex shapes (e.g. filigree structures or organic shapes) are to be modeled. Zerdad and Paulino (2014) impressively demonstrate the application of digital manufacturing for the production of models with organic shapes in the topology optimization of bridges.

As Hull and Willet (2017) show, the 3D-printed models can be used meaningfully for different functions in all areas of the development process, from the first draft via concept studies to the presentation model. By physically mapping of large quantities of virtual CAAD data, the big data can be better represented and made more comprehensible. Implementing models at different scales using parameters as well as mapping different textures and materials using Digital Materials is demonstrated by Junk and

Gawron (2018). However, as Meijs (2014) explains, the reality is different. Many architects are still hesitant to make the leap to 3D printing. In the daily practice in architecture offices, cost and complexity are usually the biggest hurdles.

METHODOLOGY

There are still some challenges that prevent the introduction of Direct Digital Manufacturing in the production of architectural models, especially in small and medium-sized architectural firms. One of the technical challenges is to find a suitable method for architectural models out of the large number of available AM methods. In addition, requirements for data preparation for 3D printing are unknown. However, there are also economic obstacles. This means that in many cases the time required for data preparation can only be estimated poorly. Furthermore, the cost of a model are unknown. Similarly, the cost differences for different AM methods are difficult to assess.

Figure 1
Design of the family house designed using CAAD-system Archicad

Therefore, this contribution demonstrate how to prepare the data from 3D-CAAD for 3D printing. In a case study, a one-family detached house as a typical project for an architecture firm of small to medium size is chosen. In order to investigate the additive methods with regard to their potential for the production of three-dimensional architectural models, a project from the architects office IFP² will be made available and then 3D printed in a print-ready manner. The 3D CAAD dataset is then produced using two different 3D printing technologies to compare the procedures. The CAAD modell represnts detached house with the dimensons of 22.27x15.31x9.98 meters , which consists of four floors. The house is divided into a basement, ground floor, upper floor and attic. The CAAD model also contains a 3D terrain model, which measures 28.99x19.94x6.92 meters. The widely used ArchiCAD software is used for design and data preparation.

Whitin the case study is analyzed which elements from CAAD are transferred to 3D printing and which elements can not be displayed due to particular restrictions (e.g. insufficient wall thickness). Subsequently, the data processing takes place in preprocessing of the printer software. To do this, the easily accessible software, e.g. or Mircosoft "3D Builder" or Autodesk "Netfabb", is used. Here, the feasibility check and the setting of specific 3D printing parameters are carried out. This model, as shown in Figure 1, is the result of a design in the CAAD program Archicad and is printed at a scale of 1:100 in the experimental procedure. In consultation with the company IFP², the model is manufactured at the University of Applied Sciences Offenburg using the methods Binder Jetting and PolyJet Modeling.

DATA PREPARATION IN PRE-PROCESSING

The first step of the data preparation carried out using a CAAD program. Once the formal requirements have been met, the 3D model must be transferred to a repair software in order to carry out further necessary reprocessing. Finally, the simplified and also checked model is transferred for Direct Digital Manufacturing in the 3D printer software. This process chainis illustrated in Figure 2.

In order to be able to produce the 3D data of the architectural models by means of 3D printing, it is important to first display only the relevant components and to hide furniture, plants and other facilities. In addition, it is also of great importance to determine the allowable size of the resulting 3D physical model. If the model should then be too large,

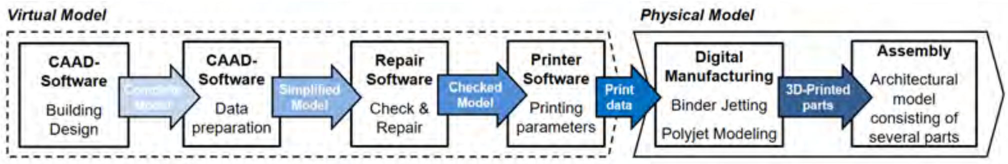

Figure 2
Process for Direct Digital Manufacturing of Architectural Models form CAAD to 3D model

one can separate it using one or more sections. In addition, requirements for the wall thicknesses and a "solid model" are important features that must be considered in the preparation in general.

Since downsizing from an original model tends to make the walls, columns, railings, windows, and doors too thin, an appropriate adjustment must be made to the model file. It is therefore important to provide the model with sufficient wall thickness or to thicken certain walls so that the minimum requirements of the respective printer can be met. Finally, to use a 3D Archicad model for 3D printing, the model must consist of one component or "solid model". As long as the individual components are only linked with each other, they also remain different components.

DIGITAL MANUCATURING

The digital manufacturing of the models uses two different, easily accessible 3D printing methods. On the one hand, Binder Jetting (BJ) is used, which works with a simple mineral building material and offers a high 3D printing speed. The 3D printer used in this contribution (Projet660 Pro by 3D-Systems) is a full-color printer with a build size of 254x381x203mm. First, a powder bed is made of a polymer gypsum powder, to which then a binder and, if necessary, also colour is sprayed on with the help of nozzles. The 3D printer advertises with its high resolution of 600x540dpi, uses environmentally friendly materials and is according to the manufacturer for architects the ideal choice. This makes it possible to produce photorealistic models through precise and consistent color gradations. It offers a fast print speed, which can be accelerated up to 28mm/h by the use of "stacking functions" and choosing the printing mode "monochrome".

On the other hand, this case study also uses the Polyjet Modeling (PJM) process, which is characterized by high 3D printing quality as well as long 3D printing times. The 3D color printer (J750 from Stratasys with a build size of 490x390x200 mm) can create over 500,000 colors with a resolutiion of 600x600x1800 dpi. The structure is achieved by the direct jetting of a photopolymer, which is cured with UV light. A special feature here is that it can be

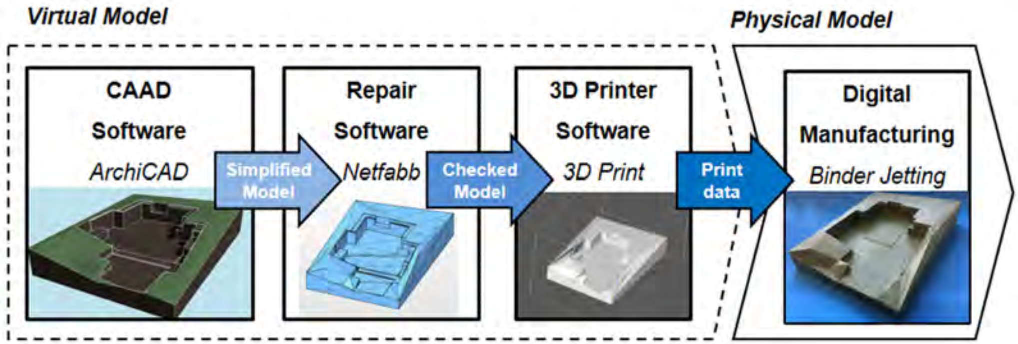

Figure 3
Application of the process chain for the Direct Digtial Manufacturing of a terrain modell

printed transparently. The 3D printer can process up to six materials at the same time and guarantee a high level of detail with layer thicknesses of only 14 microns as well as a smooth surface. The the small layer thickness results in relatively slow speed of 80 grams per hour.

This process chain is explained using the example of the terrain model representing the construction site (see Fig. 3). In this example, the 3D terrain model is first exported in STL format at a 1:100 scale from Archicad , that represents the target state. Subsequently, this file is opened in the two differnt repair software programs "3D Builder" and "Netfabb" and then described by screenshots. By subsequent transfer in the printer software programs "3D Print" (BJ) and "GrabCAD" (PJM), the model shows some more edges in comparison to the target state. However, there is no serious difference between the transferred files and the target state.

TECHNICAL RESULTS

With regard to the technical results, the building was printed once each in color and in monochrome using BJ and once in monochrome using the PJM process. In addition, the colored building is imported for testing purposes in the printing software "GrabCAD". To do this, the model is first exported as STL (geometry only), as well as VRML file (geometry and texture) and then edited or repaired in Netfabb. In all cases, good 3D printing results and a high qualitiy of appearence were achieved. Also, the terrain model is then printed once in monochrome and once in color mode. Before, the colored terrain was colored and textured via Netfabb.

ECONOMIC CONSIDERATIONS

A comparison of the methods reveals the significant economic differences of the two AM methods for use in the production of architectural models. The costs of printing, materials and personnel are considered

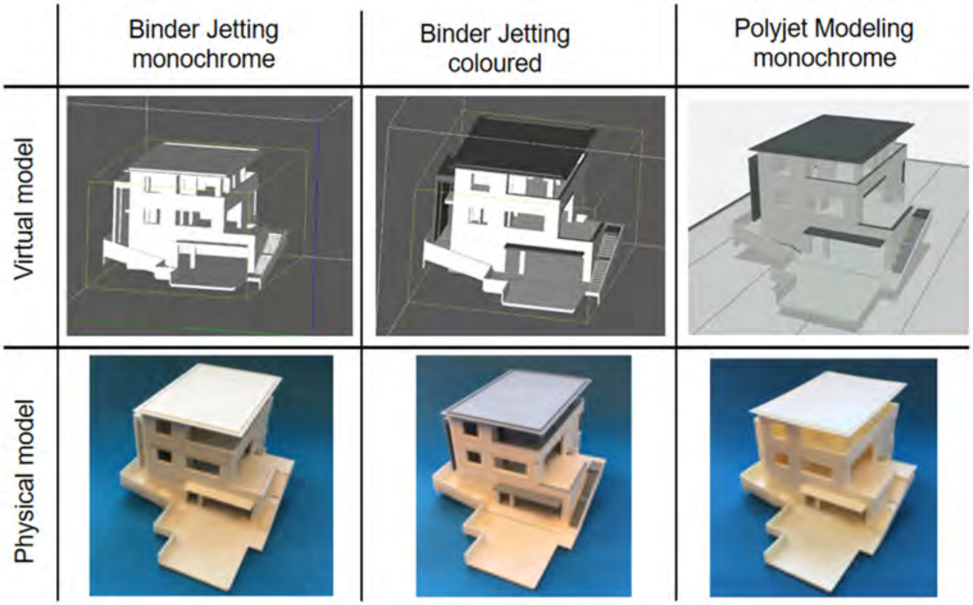

Figure 4
Comparsion of technincal results form Binder Jetting and Polyjet Modeling

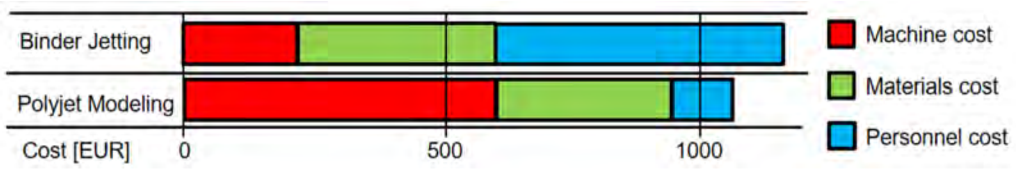

Figure 5
Cost for architectural model of detached house (scale 1:100) using Binder Jetting and Polyjet Modelling

in this comparison. The printing time has an important influence on the printing costs. This differs significantly in both methods. While in the BJ a 3D printing time of about only 6.6 hours for the house model, the 3D printing of the house using PJM method required more than 36 hours in total. In materials cost, volume is the most important influencing factor. The volume of the house amounts to approximately 384 cubic centimeters. For personnel costs, above all the time required for reworking, ie the removal of superfluous powder (BJ) or the support structures (PJM), is important. This time expenditure lies with the house model for BJ with approximately 7 hours, with the PJM only 2.7 hours. Figure 5 illustrates the cost of the house model. The cost are calculated as the average of several offers. It shows that the costs for PJM models, despite the long production time, are slightly lower than the BJ method.

DISCUSSION

This contribution shows that architectural models can be produced using modern digital manufacturing techniques. The necessary 3D models can be derived with only little effort directly from the CAAD software by hiding unprintable areas. In addition, a seperation into floors and terrain model, which are printed separately is possible. The examination of the preprocessing has shown that various software packages are available for repairing the 3D data and for setting the printing parameters. Here a suitable choice of the interfaces and data formats for the data transfer has to be considered. 3D printing provides very pleasing results in both methods. In the cost analysis, the costs for 3D printing, materials and reworking were analyzed. This case study showed a slight cost advantage for the PJM process.

ACKNOWLEDGMENTS

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Additive Manufacturing of Ceramics

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Additive manufacturing (AM) is vastly developing across the industrial landscape and has recently expanded outside of the traditional polymeric and metallic-based materials. Ceramics are an ever-present material in the architectural field, but there has been minimal evolution in its associated manufacturing processes. The limitations of additive manufacturing of ceramics are quickly evolving and will soon create new potentials for architectural products and applications. This paper offers an overview of these limitations that are tested and examined through a case study.

Keywords: *Additive Manufacturing, Ceramics, Robocasting, 3D Printing*

INTRODUCTION

Ceramics are a novel material that have been utilized in constructed environments for centuries, and until recently have been restricted to traditional modes of craft when applied at the scale of architecture. Casting and extruding have been the primary methods of ceramics manufacturing in the building materials industry. These traditional manufacturing techniques have limited the potential of ceramics across the allied design fields. In observation of rapid advancements in digital systems of production and fabrication, it only feels appropriate to apply these advancements to a material that has been ever-present yet primitive in the field of architecture. Hybridizing conventional methods of production with the rapidly expanding arsenal of digital tools available today will open new avenues for ceramic applications in the field of architecture.

Ceramics are an inherently attractive building material due to the rare combination of exceptional mechanical, thermal and chemical properties (Faes 2015). However, traditional modes of manufacturing in the ceramics industry have limited the potential for mass-customized components. High costs associated with unique molds and lengthy production timeframes are just a few of the constraints that have stifled the production of geometrically complex ceramic components. "The production of highly complex 3D shapes, micro features, or structures with tailored porosity, such as scaffolds, is still seen as a major limit" (Faes 2015). Additive manufacturing of engineered ceramics can vastly expand the current range of production possibilities.

ADDITIVE MANUFACTURING PROCESSES

Up until this point, most work and research on additive manufacturing have been centered on polymers and metals. Additive manufacturing of ceramics is significantly less developed, and therefore ripe with potential for further investigation and research. There are several additive manufacturing processes that are currently being utilized and developed in the ceramics industry. Stereolithography (SLA), Lithography-based Ceramic Manufacturing (LCM), Freeze-Form Extrusion (FFE), Selective Laser Sintering (SLS), Fused Deposition of Ceramics

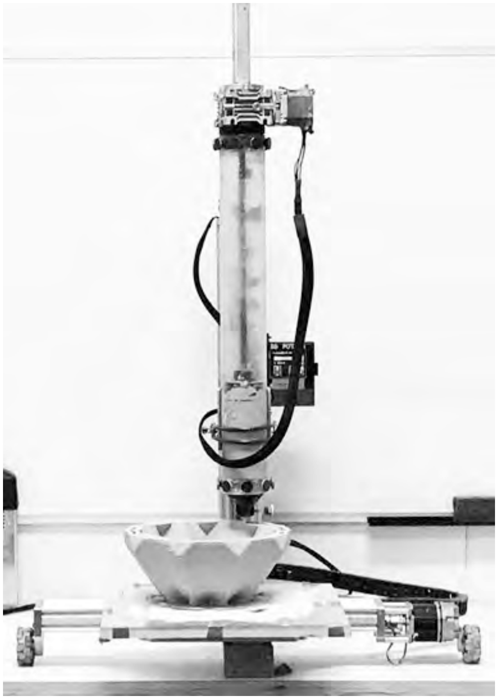

Figure 1
3D PotterBot in the process of printing

Figure 2
G-code line drawing of a 2mm z-step

(FDC) and Robocasting have all been investigated for their feasibility in the production of ceramic components (Faes 2015). Robocasting will be the focal process in the case studies outlined in this paper.

Robocasting is an additive manufacturing technique in which a filament or paste is extruded from a nozzle onto a fixed or dynamically controlled platform. Objects are produced by adding material in a layer-by-layer fashion where either the nozzle is moved up or the platform is moved down. Unlike many consumer grade 3D printers that print via fused deposition of thermoplastic filaments, robocasting relies on surface tension to fuse each layer together (Feilden 2016). There are no thermal gradients involved during the robocasting process, and the extrusion pressures are much less than fused deposition modeling (Feilden 2016).

CALIBRATION CONSTRAINTS

There are many variables to consider in the robocasting manufacturing process of ceramics. The stepover and angle of cantilever without additional formwork or support structure is an ever-present constraint. In fused deposition thermoplastic prints, 45 degrees tends to be the maximum angle one can achieve without secondary support structure. These constraints were investigated over a series of case studies conducted with a 3D PotterBot from DeltaBots. A concentric multifaceted geometry was designed in Rhinoceros to specifically test and calibrate an array of material constraints. The subject artifact's geometry is a composition of curved and flat surfaces that both undulate and cantilever at various degrees. Simplify3D was utilized as the slicing software to generate the g-code for the 3D PotterBot. Paste composition and environmental conditions during the printing and drying period had major effects on these tests. Several trial prints with various sized nozzles were conducted, and subsequently a 4mm circular nozzle was found suitable due to its consistency. A z-step of 2mm was found to provide sufficient adherence to the previous layer. With these calibrations, a maximum cantilever of 30 degrees was achieved over a four-inch tall outward sloping concentric print; significant slumping and failure occurred in cantilevers larger than 30 degrees. Further, secondary supports must be printed or introduced to support most cantilevers and overhangs. Depending on the paste composition, printing speed and printing environment, robocasting can typically deal with large spanning regions many times the filament diameter in length, where the structure is unsupported from below (Smay 2002).

Figure 3
30 degree cantilever from base that rises 4”

Additionally, paste composition is fundamental to a successful robocasted print. The slurry or paste must be suitably homogenous and free of air bubbles and agglomerates (Feilden 2017). To eliminate air bubbles from the ceramic paste and ensure a consistent paste a de-airing pugmill was utilized to process the paste for our investigations. This tool utilizes a vacuum to remove air bubbles from the paste and extrudes a consistent cylindrical volume of paste directly into a clear plastic tube which is then loaded into the 3D PotterBot. Even when processing the paste with the de-airing pugmill a low percentage of air bubbles remained and produced inconsistencies in each print. The tube’s volume capacity proves to be a constraint because without a continuous feed significant drying of the clay occurs during the unloading and loading of each tube into the PotterBot’s RAM extruder. This results in the new layer not bonding uniformly to the last layer of the previous tubes print. The z-height calibration when loading a new tube also proves to be troublesome when attempting to print with multiple tubes as the last clay layer settles during the tube interchange. This produces a noticeable inconsistency in the horizontal banding at this layer. This inconsistent banding is problematic both visually and in performance. Therefore, our studies were limited to single tube print volumes under 1500000 mm3.

Furthermore, the viscosity of the paste must be low enough to allow for extrusion through the printer’s nozzle, but stiff enough to hold its shape and allow each new layer to bind with the previous layer. The ratio of ceramic powder to water must be high in order to achieve high green densities which reduces drying shrinkage and allows complete sintering (Feilden 2017). Pastes containing up to 60% volume of ceramic particles have been successfully employed (Faes 2015). There have been several studies executed on highly engineered pastes with additives such as gels, resins, deflocculants and fibers to ensure a high degree of printability with minimal shrinkage (Feilden 2016). Aqueous pastes are desirable due to their simplicity, lower cost, low toxicity and slower drying periods (Feilden 2016). Therefore, in our case studies we focused solely on aqueous pastes and developing an appropriate ceramic powder to water ratio.

MATERIAL AFFECTS

One of the unfortunate results of utilizing a 4mm nozzle tip with a 2mm z-step is the distinct staircasing affect that is produced via this layered manufacturing process. Additionally, there are a number of defects that are fairly commonplace in the manufacturing and processing of ceramics: agglomerates, bubbles, contaminates/inclusions, and large grains occur quite frequently (Feilden 2017). Subsequent machining in the green unfired stage is required to achieve

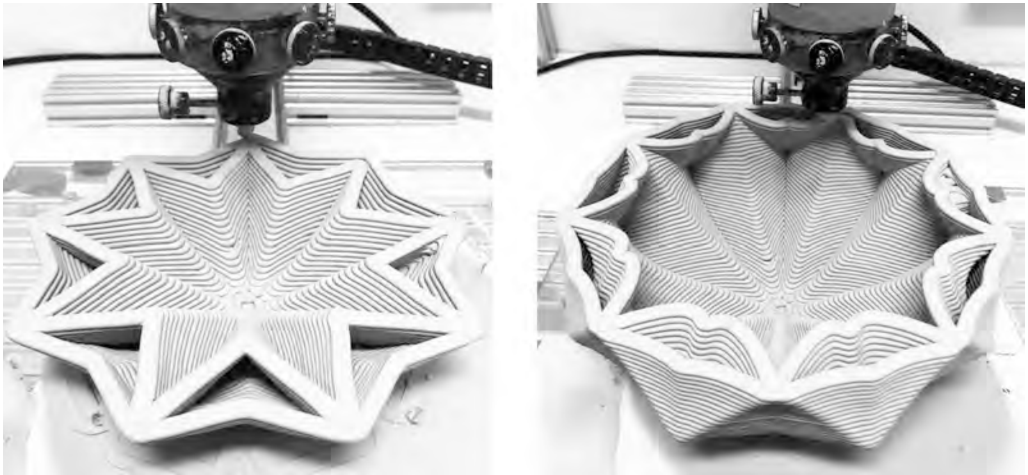

Figure 4
Detail views of a print in process. The concentric surfaces intersect at critical moments and create lateral stability.

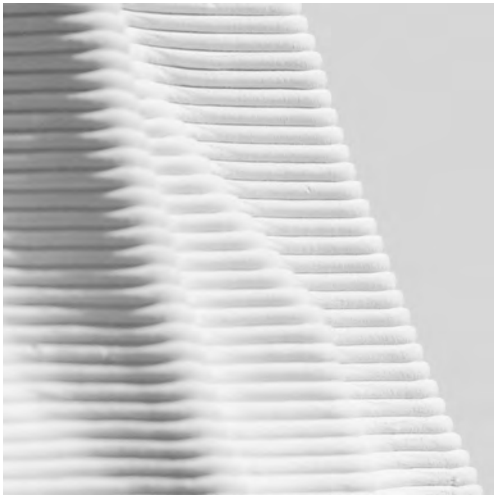

Figure 5
Staircasing affect from a 4mm nozzle tip with a 2mm z-step

smooth surfaces before bisque firing or sintering occurs. This process is known as green machining and is heavily employed in the rapid prototyping of ceramic components (Riedel 2011). Green machining introduces its own array of unpredictable flaws like chipping, cracking and edge retention as the material is very fragile in this phase (Riedel 2011). The consistent recurring presence of these material flaws is one of the major hurdles researchers and manufactures are attempting to overcome. A majority of these flaws are not necessarily removed during the firing phases and are therefore present in the final product (Riedel 2011).

Minor surface defects that are not removed during the green machining phase can be further diminished through glazing techniques. Glazing produces a highly resilient waterproof layer that is generally desired in architectural applications. There is a material thickness that is added with ceramic glaze which needs to be accounted for in joint tolerances. This added material thickness coupled with the varying degrees of shrinkage during the firing stages are what make this material historically imprecise. The glazing material thickness is also what smoothens over minor surface defects. During this case study two glazing techniques were tested for consistency. Dip glazing and airbrushing were both tested on several iterations in varying degrees of thickness. It both instances the base of the artifact was coated with wax to prevent the glaze from adhering to the base. This ensures that the glaze will not fuse the object to the kiln shelves during the firing process. Alternatively, kiln spurs can be utilized if one requires the object to be entirely glazed. Ultimately, airbrushing the glaze provided a higher level of control over the dip technique. Applying three light coats with the airbrush produced a high-quality finish without adding substantial thickness.

Traditional kiln firing and sintering of aqueous ceramic paste prints proves to be challenging as substantial shrinkage occurs, which at times leads to cracking (Faes 2015). Calibrating this shrinkage has proven difficult in mass customization projects as each component is usually varied in its material composition and structure. This is why traditional modes of production such as extrusions and slip casting of uniform geometries continue to be the dominate techniques utilized in ceramic manufacturing. Highly engineered composite pastes that minimize shrinkage and manufacturing flaws continue to show the greatest potential for additive manufacturing of mass customized ceramic parts. However, many of these newly formulated pastes have yet to be implemented beyond the research phase (Feilden 2016). This research is critical if robocasting is to be used industrially where defect distributions are central to understanding a part's reliability (Feilden 2016).

The time required in the firing sequence also proves to be an ever-present constraint in the additive manufacturing of ceramics. Each artifact produced in this case study took a minimum of five days to produce. This process consisted of (in sequential order): the wet printing phase, 24-hour dry time, green machining, 12-hour bisque fire, 8-hour cooling, glaze application, 24-hour glaze fire and subsequent cooling. The factor of time in the manufacturing of ceramics is being tested through various other alternative modes of additive manufacturing. Stereolithography (SLA) has shown promise with employing a UV-curable resin as a binder which is mixed with the ceramic powder to create an engineered paste (Faes 2015). In this process the resin is cured by means of a UV-laser as it is dispersed. This instantaneously generates a green product, cutting out the bisque firing and cooling phases. The printed green body is then machined, glazed (if desired) and fired. While this dramatically reduces the overall time required, it is both cost- and material-inefficient (Faes 2015).

CONCLUSION

In conclusion, the imprecision of robocasting ceramics has limited the employment of ceramics in mass customized parts and components across the architectural profession. The robust material properties and cost effectiveness of ceramics are undeniable.

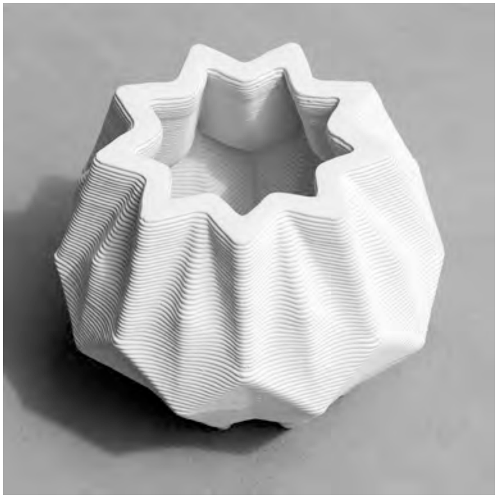

Figure 6
Subject artifact after green machining and subsequent bisque firing.

Figure 7
Case study iterations

Rapid advances are being made in ceramic paste/slurry compositions as well as in the sintering processes that minimize material imprecision and time duration. However, these processes still prove to have technical issues and are cost prohibitive at the scale of architectural components. Advances are quickly being made, and therefore is only a matter of time before these hindrances are removed where additive manufacturing technologies become widely adopted across the ceramics industry and subsequently, the architecture community.

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Semi-flexible Additive Manufacturing Materials for Modularization Purposes

A modular assembly proposal for a foam edge-based spatial framework

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This paper introduces a series of design and fabrication tests directed towards the use of bendable 3D printing materials in order to simplify a foam bubble-based geometry as a frame structure for modular assembly. The aspiration to reference a spittlebug's bubble cocoon in nature for a light installation in the urban context was integrated into a computational workflow conditioning light-weight, material-, and cost savings along with assembly-simplicity. Firstly, before elaborating on the project motivation and background in foam structures and applications of 3D-printed thermoplastic polyurethane (TPU) material, this paper describes the physical nature of bubble foams in its relevant aspects. Subsequently this is implemented into the parametric design process for an optimized foam structure with Grasshopper clarifying the need for flexible materials to enhance modular feasibility. Following, the additive manufacturing iterations of the digitally designed node components with TPU are presented and evaluated. Finally, after the test assembly of both components is depicted, this paper assesses the divergence between natural foams and the case study structure with respect to self-organizing behavior.

Keywords: *digital fabrication, 3D Printing, TPU flexibility , modularity, optimization*

CONTEXT

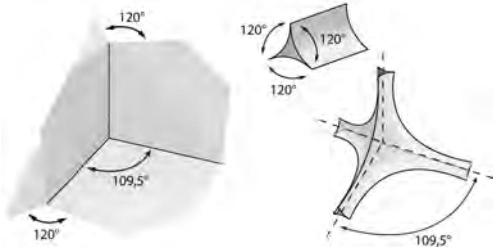
Within the context of the research project "GetHome-Safely" the experiment was to design an urban night light to be installed and tested in variable notably dark spots around the city where conventional street light glow does not reach out to. GetHomeSafely is an Innovation Activity supported by EIT Digital offering a human-centered and IoT-based network lighting that guides you through those dark areas.Further contexts as well as relevant requirements the project is touching upon are outlined in the following. A) Envisioned Design: The envisioned design for an irregular light-weight frame structure is inspired by and references the geometric principle of the cocoon of a spittlebug. The cocoon of a spittlebug is a bubble blob usually created at a bifurcation of leaves or blades of grass (Figure 1a). It is made from multiple spit bubbles that agglomerate in a similar fashion as soap bubbles do, resulting in a three-dimensional ‘body’. When foam bubbles are connected, three or four foam edges always meet at one intersection. These multiple intersection points are distributed according to a three-dimensional Voronoi principle (Vecchio, Redenbach, Schadelitz, 2014). The project looks at the edge condition of the spittle bug’s bubble cluster and mimics its geometry (Figure 1b). B) In architecture, the Voronoi principle has mostly been employed for 2D surface division. Large scale architectural applications of materializing foam edge geometries have rarely been accomplished, yet the Beijing National Aquatics Center by Herzog & de Meuron is a successful counterexample in rigidity (Senses, 2007). In an installation scale, Thomas Saraceno’s ‘Entangled orbits’ exhibited in the Baltimore Museum Museum of Art 2017-2019, mimics dry foam agglomerations that simply stay balanced through tension and suspension in space [1]. C) Material: We chose light-weight materials to enable an environmentally sound design concept. Especially in 3D printing, explored material properties inform the computational design workflow and fast prototyping eliminates the risk of an insufficient completed mass production. D) 3D Printing Technology with TPU: Evaluating the use of 3D printed Thermoplastic Polyurethane material, it is striking that it has predominantly been applied in the digital fashion industry and medical research. Most designs are soles or midsoles for shoes, fine web fabrics for bendable light-weight dresses or tests for prosthetic elements in need of tensile strength. Within the do-it-yourself community, TPU is neither used in a large additive scale, instead for phone cases, costumes or replacement parts in mechanical applications.

Figure 1
a. Spittlebug’s cocoon (www.ecoyards.com)
b. Envisioned application of referenced structure

SPATIAL ORGANIZATION OF FOAMS

Foams are gas cells enclosed in liquid film. Foam bubbles emerge in polyhedral cells with their liquid film walls meeting in lines (edges) and intersecting at vertices (nodes). Three gas cell films always meet along one edge and four edges always intersect at one point (Figure 2a). Foams are self-organizing structures that form a static equilibrium when rather dry and under normal gravitation (Hutzler, 1997).In a biological context it is distinguished between dry foams and wet foams characterized by the parameter of liquid fraction (Waire et al, 2001). A foam is called ’dry foam’ when it has very little liquid and the soap films are so thin that the liquid only exists interstitially at the foam bubbles’ points of intersection (Mancini, 2005). The equilibrium of dry foam constitutes in the so-called Plateau’s laws, experimentally established by the physicist Joseph Plateau and mathematician Jean Taylor in 1976. The characteristics of this state relevant for this research are: 1. Soap films, figuratively surfaces, invariably meet in threes at an angle of 120°, the Plateau border (Figure 2a). 2. This intersection of four vertices in three-dimensionality with the same angle constitutes in a tetrahedral vertex node. The vectors from a tetrahedron’s geometrical centroid to the four vertices interrelate in a 109.47° or cos-1(1/3) angle (Figure 2b) (Hutzler, 1997: p.22).

Figure 2
a. Plateau's equilibrium rules in dry foam polyhedral cells b. Plateau's ideal dry foam border in cross-section and perspective



Through the liquidity of the foam and its pressure being bigger than the one on the borders, the cross-section of is organized in concave triangles. Within this phenomenon of self-organization and equilibrium of dry foam it is important to keep the following in mind: Since the gas cells are of different size have varying edge lengths, the bubble edges are no straight two-point lines in the equilibrium state geometrically defined by Plateau. The edges arbitrarily adapt their route in space to form the perfect tetrahedral vertex intersection. For this experiment, the foam structure is broken down to the foam cell edges and their intersections, leaving the film surfaces unconsidered.

MODULARITY AND VARIETY

Structurally mimicking the variety of 3D Voronoi edge intersection nodes spawns a difficulty in assembly due to every single node being bespoke. To minimize planning, production and assembly complexity as well as costs, modularity in the build-up is inevitable.We developed a system with two generic modular components (Figure 3) that are nodes and linear connecting edge elements, in a number of variations. They are defined as follows: The rod embodies the foam cell edge up unto the intersection point. The node is the entire joint that builds around the intersection point of the cell edges in a three-dimensional environment. Its center point is the exact intersection point of the cell edges. This encases the rod ends in a shaft at a fraction of their length.

The node component design is elaborated in the following chapter. The experiment is set up to emphasize on modularization of the bubble foam geometric principle: firstly, through computational alterations and secondly, through physical material properties and the exploitation of material behavior. Through a combination of geometry and material properties we are achieving semi-flexibility allowing the angles between the foam edges to further adjust to the overall network.The modularization entails a limited number of different types of nodes (Figure 4), limited angles between the rod shafts as well as a progressively limited length of the hollow shafts. It also necessitates an incremental limit to the rod lengths representing the distance between the nodes' center points. It is apparent that various configurations of the nodes and rod lengths reveal a visually varied pattern from a foam edge distribution and consequently show a different structural behavior.

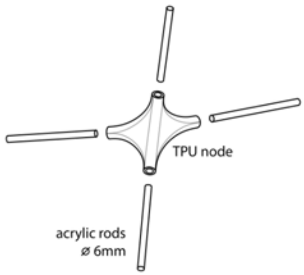


Figure 3
Modularity through two components: nodes and rods

COMPUTATIONAL FORM DETERMINATION AND GEOMETRY

Firstly, a digital twin of a representative dark corner in the city is modeled in 3D and within boundaries randomly populated with points in Grasshopper. This allows for two options for the subsequent form finding step: a) The points serve as the input points for a Grasshopper 3D Voronoi component. The angles and distances of the edges are modified thereupon. b) The points are connected by curves and determine the angles and distances of the curves. This represents a manual build-up of the structure.Here, we tested option a) to stay close to the principle of a foam geometry. The following experiment description clarifies that the initially set amount of points neither determines the density of the frame structure nor the amount of nodes. The cell surfaces generated by the 3D Voronoi component are left unconsidered and the cell edges are deconstructed and organized as curves with intersection points in data lists.Aforementioned, in an equilibrated dry foam the cell edges do not represent straight lines intersecting in a tetrahedral angle. In contrast, the computationally generated 3D Voronoi frame by Grasshopper sets up straight lines as A to B vectors, since the system cannot undertake and simulate the chemically motivated self-organization. The resulting angles between each four cell edge curves intersecting vary approximately between 60° and 140° as a general rule. While constraining the angle parameter between these edge curves, it is essential to distribute between direct and indirect neighboring curves at the vertex. The domain limiting the angle only applies to the two directly adjacent edges, not the opposite one. What are we setting the domain to 85° to 130° considering the tetrahedral state of all angles at 109,47° (Figure 4).

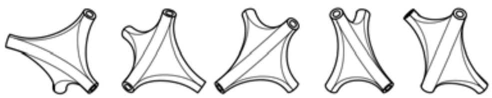


Figure 4
Joint variations generated by Grasshopper

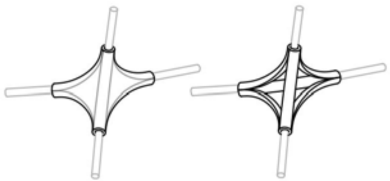


Figure 5
Smoothened connections with and without skin (skeleton)

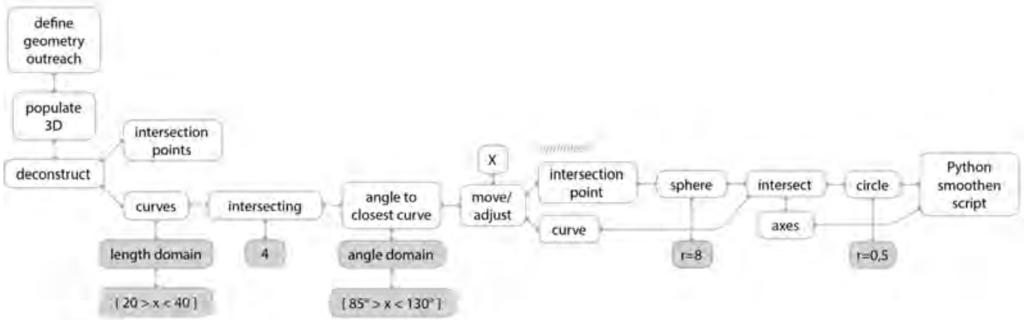
The subsequent operation is setting a restriction to the foam bubble edge length. This domain defining the length of the cell edge curves entails purging curves outside of it. Since the length of each edge curve is determined by its end and start point, any change of length in order to meet the requirements would again affect the angles and the entire point cloud. To relax these, the points have to allow for movement through the angle adjustments. As for the prototype, the domain is set between 20cm and 50cm for the acrylic rods. The optimization of the edge curves automatically sets the construction axes of the nodes. They are further parametrically designed by a script in Python for Grasshopper to smoothly connect the shafts for the rods around the center point (Figure 4 and 5). The node shafts are computationally restricted in length according to the overall edge curve length. This parameter will have a notable impact on the overall flexibility of the entire node.

The further the semi-flexible filament encases the acrylic rod the more flexibility is given since TPU bends easier than the acrylic resin.To be proportionally dimensioned to the acrylic rods and speed up the production process for testing, the maximum span of the tetrahedron based joint will be approximately 8cm. Computational form finding was exploited to generate various exemplary nodes rather than defining a typical node and the Grasshopper optimization does not output a certain number of different types. Choosing a few nodes from the system for production ensures a final structure built in irregularity. Regularity cannot be expected from our single-rule modular build-up.

ADDITIVE MANUFACTURING OF THE FLEXIBLE NODES

There is a variety of technologies in additive manufacturing that can be attributed to four different categories by the material used: photopolymer-curing, granular, lamination and fused deposition modeling (Fastermann 2016); and each one entails specific fabrication attributes, opportunities but also constraints. For this experiment fused deposition modeling FDM technology or also called fused filament fabrication FFF is performed with an Ultimaker 3, where the material filament is heated in the print core, expelled through a brass nozzle and deposited in layers to build up the model.

Figure 6
Grasshopper
optimization logic



1. TPU filament for node pliability

A formerly outlined condition for the physical node that the product is bendable. To test the semi-flexible material behavior for the designed node one selected node was repeatedly printed with varying print settings. These prototypes were performed using Ultimaker TPU 95A material extruded through a brass nozzle of 0,4mm in diameter. The thermoplastic polyurethane filament is a composite material from rubber and plastic. It is a semi-flexible and chemical resistant material with strong layer bonding [2]. TPU consists of a microstructure that contains both hard and soft copolymer segments within the polymer chain. These different types of segment domains in the two-phase structure have “a significant impact on the tensile strength and elongation of the [TPU] material”. Through FFF extrusion in the 3D printing process, the hard segment domains in the TPU can change their length. (Hohimer et al, 2017). This means that the mechanical properties of TPU, especially the tensile strength, change through 3D printing. Polyvinyl alcohol filament, PVA, a water-soluble support material was used on the second extruder for the support build-up for the node [3].

2. Print parameters

Cura is the corresponding software for Ultimaker 3D printers to set print settings and write G-codes. For the 3D printing tests, the parameters summarized in Figure 7 were modified iteratively. To test general bending properties with respect to layer bonding of TPU from an extrusion-based print, primitive forms like columns were printed. The result showed a strong layer bonding without ripping under high tension, but it was explored that the infill and its layout, in spite of consisting of TPU, too, negatively affect the pliability.

To reduce a risk of failure such as non-adherence to the previous layer, technical machine variables such as extrusion speed, printing temperature and retraction speed were modified. To test the pliability of the product material, layer height, layer thickness and infill pattern and density were varied. The fabrication monitoring until then showed that the technical settings for the extruder mostly resulted in faulty prints. Just as in the primitive test shapes, it was observed that the material-related variables, especially the infill, impact the flexibility significantly. The concentric infill pattern (Figure 8a, Figure 8b) as offset surfaces to the outer skin proved to be beneficial for pliability (P4-P6 in table). The air gaps between the infill layers offer space to be compressed once the rod shafts are moved different directions.

Printing Iteration		recom-mended by Ultimaker website	P1	P2	P3	P4	P5
Ultimaker 3 Setting	**Unit**		**normal 0.15mm**	**fine 0.1mm**	**normal 0.15mm**	**normal 0.15mm**	**normal 0.15mm**
Layer Height	mm		0.15	0.1	0.15	0.15	0.18
Initial Layer Height	mm	0.27	0.15	0.15	0.27	0.27	0.27
Line Width	mm		0.38	0.38	0.38	0.38	0.38
Shell: Wall Thickness	mm	0.76	0.7	0.7	0.76	0.5	0.7
Shell: Top Thickness	mm					0.66	0.7
Shell: Bottom Thickness	mm					0.7	0.7
Infill: Infill Density	%	10	15	15	18	20	20
Infill: Infill Pattern			Cross 3D	Cross 3D	Cross 3D	Concentric	Concentric
Printing Temperature	°C		225	225	225	225	225
Build Plate Temperature	°C		60	60	60	60	60
Print Speed	mm/s		25	25	25	25	25
Retraction Speed	mm/s		off	off	35	35	35
Retraction Travel	mm		off	off	0.76	0.76	0.76
Support Overhang Angle	degree				45	45	45
Support Density	degree				40	20	20
Support Pattern					Triangles	Triangles	Triangles
Printed result			**failed**	**failed**	**not flexible**	**ripped walls**	**thin walls**

Figure 7
Modified Ultimaker 3 settings in the prototyping phase

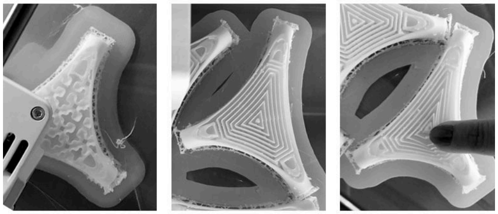


Figure 8
a. Cross 3D infill pattern of 3D printed flexible node b. Concentric infill pattern of 3D printed flexible node c. Concentric infill pattern pushed for flexibility test ©TheresaLohse

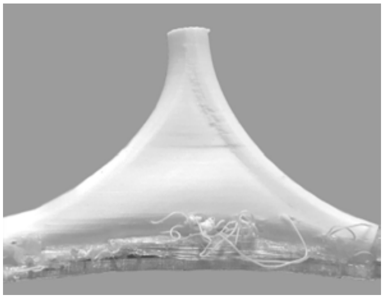


Figure 9
Outer wall thickness showing rupture ©TheresaLohse

However, due to the positioning of the geometry on the build plate of the 3D printer, the direction of pliability allowed by the concentric infill varies for each shaft since the infill is technically set up on two axes only. As an alternative pliability test, the skin and infill were removed and only the geometry skeleton (Figure 5) was printed with a diameter of about 6mm. The print failed and demonstrated remarkable stability deficits. As summarized in the print parameter table (Figure 7), prints progressively turned out more adequately. However, there is a visible inconsistency and rupture (Figure 9) in layer bonding and adhesion in the outer wall build-up. This showed to be a risk especially in assembly with the acrylic rods that channel the tension force more concentrated on the axes of the node. As a conclusion for the 3D printing process, TPU solely as a material did not prove sufficient flexibility for our application, instead it is a mixture of interior and exterior geometry setup of the node and the semi-flexible material. The wall thickness and density as well as the retraction speed of the nozzle had to be carefully adjusted to reach satisfactory results.

Figure 10
TPU node flexibility in structure assembly
©TheresaLohse

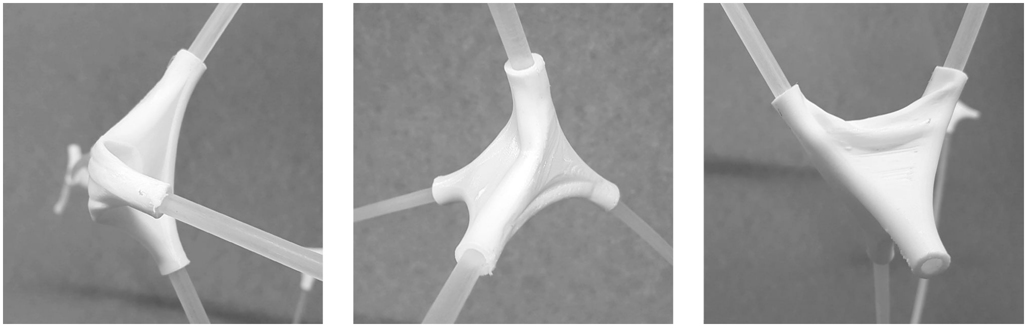


Figure 11
Test assembly of both modules
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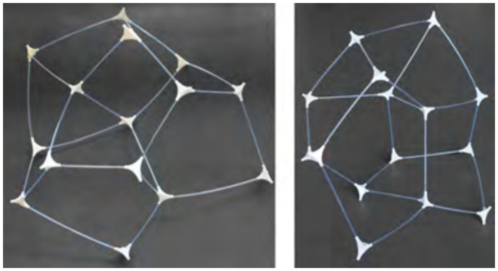

ASSEMBLY AND FLEXIBILITY TEST - DISCOVERIES

This research targeted generating an irregular modular node and rod structure referencing bubble foam in a simple assembly for anyone in any place. The two modules are stuck together in a simple fashion without additional adhesive. The rods were manually cut to 4 different lengths of 20cm, 25cm, 30cm and 35cm to reduce production complexity. During assembly, it was discovered that we are dealing with a divergent self-organization of the structure contrary to the dry foam in equilibrium. We learned that in a dry foam, the 'soft' cell edges "as a network of narrow [liquid] channels [filled with air] with a triangular cross-section" (Hutzler, 1997: p.22) adapt to the node organizing the four intersecting edges in a tetrahedral manner. The cell edges undertake the spatial adaption resulting in the tetrahedral joints. As for our assembly, the chosen acrylic rods of 6mm diameter are slightly flexible only along the center axis attributed to their shape which is dissimilar to the isotropic behavior of the liquid cell edges in foam. The stress caused by the self-organization unevenly splits up between the node and rod as they do not consist of the same cellular build-up. Nevertheless, the TPU node underlies most necessary bending in our structure whereas the acrylic rods stay fairly 'straight' (Figure 10).

Practically, an inversion of the dry foam self-organization principle exists: Node: The nodes are particularly designed closely to a fourfold junction of a Plateau borders to enable irregular adaptation to deformations. Rods: The material choice allows only minor adaption through bending. Since the TPU node complies to stress first, the rod is not challenged in equal measure. The deformation of both the TPU nodes and the acrylic rods is unpredictable and will be different in each modular assembly variation. As mentioned, the semi-flexible joints show anisotropic bending behavior rooted in the additive manufacturing set-up (Figure 11). This combination of two semi-flexible materials induces general bending rigidity in the assembled structure. However, the structure does not structurally function like a conventional space frame because it is neither regular nor based on a rigidity matrix. Despite the necessity to analyze the structural soundness of the assembled structure, its overall stiffness and compression stresses are perceivable. In order to conduct a reliable structural analysis, the node has to be regular and the assembly rules for a repetition of certain n-gons have to be established and complied with.

CONCLUSION

The objective was to challenge adaption through material behavior in order to simplify the variations for production rather than exemplifying all possible node variations.The tested prototype delivered convincing results to understand the degree of flexibility in the node for a modular and unplanned three-dimensional foam node and rod structure.The visual appearance referencing a foam agglomeration is satisfactory if the number of foam edge rods do not fall below four and exceed 7. Yet, the print settings regarding layer height, line width and outer wall thickness cannot be easily scaled up proportionally to the model size. Firstly, the extruding nozzle diameter affects the limitation of the line width, albeit it is recommended to stay as close as possible to the 0.4mm nozzle width for successful prints. Secondly, the overall size of the printer is limited to 197 x 215 x 300 mm and tied to the nozzle-governed layer resolution hence, a different 3D printer ought to be used. The experiment also does not reflect upon a deep structural analysis and simulation undertaken by digital structural analysis tools. To a degree, the assembled structure stabilizes similar to the self-stabilization of a foam through self-organization of the bubbles respectively the nodes and rods. The prototype did not show a structural deficit caused by its dead load, yet when extending the structure in this scale by nodes and rods, extra stabilization might be necessary. Conclusively, the prototyping endeavors with semi-flexible material helped to reveal the impact on larger scaled constructions and installations employing an adjustable, spatial foam cell edge-led node and rod system, as very promising due to the remarkably simple and fast assembly.

ACKNOWLEDGEMENTS

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[1] https://artbma.org/exhibitions/tomas-saraceno

[2] https://ultimaker.com/materials/tpu-95a

[3] https://ultimaker.com/materials/pva

Ceramic Additive Manufacturing in Architecture

Computational Methodology for Defining a Column System

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The present paper describes a research that explores the design and production of customised architectural ceramic components defined through parametric relations of biomorphic inspiration and to be built through additive manufacturing. In this sense, is presented a case study that develops a system of both architectural and structural components - a column system. The definition process of the system is mediated by computational design, implementing not only structural analysis and optimization strategies, but also mimetic formal characteristics of nature to an initial grid, creating a model that adapts its formal attributes, depending on its assumptions and the material constraints. This process resulted in the definition of a set of solutions that better answer to a specific design problem.

Keywords: *Additive Manufacturing, Ceramic 3D, Computational Design, Structural Optimization, Biomorphism*

1 INTRODUCTION

The present research aims to contribute to the development of knowledge in the use of additive ceramic manufacturing in architecture. This research works mainly on the topics of ceramic additive manufacture and fabrication of structural components, however to develop them it interconnects with other equally important themes. Namely, the integration of computational design, structural optimization and biomorphism for the definition of structural components. The aim is to develop a column system, which acts as an auxiliary design tool, integrating the design of the respective structural components, according to certain initial conditions, and then producing it with the use of additive ceramic manufacture.

With this objective in mind it is proposed the use of computational models for the integration and control of a set of parameters - biomorphic and structural - that are intended to be the origin of the definition of the column system. Later, with the final design achieved, we aim an exploration of the structural optimization of the prototype, as well as the manipulation of the g-code and the machine.

2 DEFINITION OF COMPUTATIONAL MODEL

The development of the whole process of the column system was performed through Rhinoceros 3D, a three-dimensional modelling software, and

Grasshopper, a graphic algorithm editor native to Rhinoceros, which allowed the system to be developed parametrically.

As it was intended to explore the association of biomorphism with architecture, it was tried to explore the application of reticulated grids to the column. And so, the first question arises "How to develop this kind of grids parametrically in Grasshopper?". For this we began with an elementary geometric form to simplify the development of the parametric model.

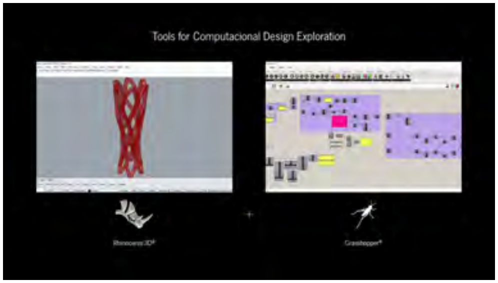

Figure 1
Tools for Computacional Design Exploration

21 CONSTRUCTIVE STRATEGY

The first strategy was the application of models that generate structural meshes, initially in a random way, from a population of points, however there was no control over the geometries generated. In order to understand the problem of this approach it is necessary to understand that the ceramic additive manufacturing process, through Liquid Deposition Manufacturing (LDM), has a condition to be taken into account. This process demonstrates a weak ability to produce objects with amplitudes greater than 30º in relation to the Z axis, running the risk of the object falling and the printing failing (Figueiredo et al., 2017). Therefore, because there was no control over the final geometries, the manufacturing through ceramic material became complicated.

In an attempt to control the generated geometries, regular grids were applied to the population of points. Thus, the final geometries that made up the reticulated grid were known at the outset. However, because they were regular, the amplitudes remained higher than 30º, and because the computer generated these forms they could not be manipulated after. Therefore, a restructuring was sought in the process of defining the cross-linked structural grid, changing the process operator, that is, instead of allowing the computer to automate the design of the cells, it was attempted to be the user to define it, ensuring greater control over the grids design.

However, the nodes between the ribs did not give a satisfactory structural continuity to the design of the prototype, due to the fact that the grid was generated horizontally around the column. Therefore, a restructure of the computational code was developed that tried to solve this question and that at the same time simplified the parametric model, because the current approach made the generation process too slow.

Thus, by maintaining the elementary basis of the prototype, we explored the definition of the reticulated grid by dividing the base geometry into subsurfaces rather than a population of points. From this, the desired pattern was drawn, and the computer applied it recursively to all subsurface surfaces, thus constructing the grid. In this way, the nodes ceased to be a problem, since the smoothing process of the grid was done vertically, guaranteeing a satisfactory structural continuity. With this, we were faced with a work base that we considered to be consistent and could continue to explore the biomorphism associated with the column.

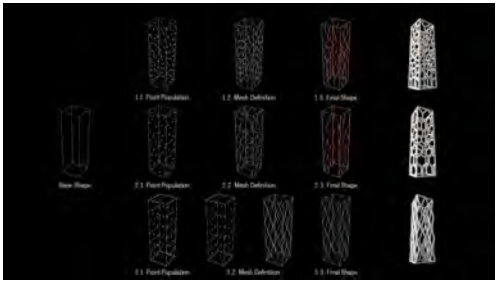

Figure 2
Constructive Strategies

22 COMPLEXITY AND BIOMORPHISM

Based on the observation of the structure of the trunks of plants, a formal mimetic relation with the Ficus plant was proposed for two reasons. First, it has been found that the design of its trunks seems to refer to a cross-linked structural grid, and secondly, because it is a plant structure, it has a great fluidity and formal organicity, so that its ridges appear to move freely. With the introduction of these features in the column system it was possible not only to consider the generation of new formal possibilities, but also to interconnect the idea of biomorphism with architecture.

To the base design of the system was applied a variation of its section along its height, as well as rotations were applied in these same sections, resulting in a design closer to the characteristics of the Ficus plant. From this moment on we had an operational parametric model, able to generate various solutions from a group of parameters that defined the column, doing it in a parametric, fast and simple way.

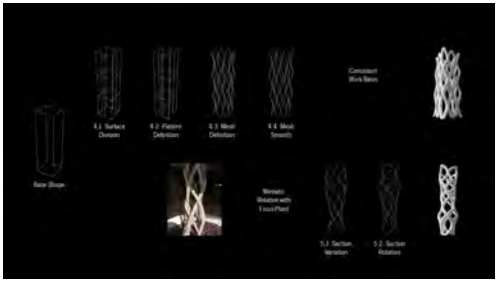

Figure 3
Strategies for Complexity and Biomorphism

23 STRUCTURAL ANALYSIS AND OPTIMIZATION

One of the themes also explored in the present paper was the structural optimization, possible through a previous structural analysis. This was possible by integrating two plugins specialized in these tasks, specifically Karamba3D, which analyses the structural behaviour of three-dimensional geometries when certain loads are applied to them. For this analysis the software works with a base of simple elements, so the first task that this one executes is the translation of the three-dimensional object to vector elements. From this we obtained the values of the weight and deformations of the column, two crucial aspects for structural optimization, because we aim to minimize these characteristics.

The optimization process was done through Octopus, which privileges the control over the development of the design of the reticulated structural grid, applying evolutionary principles to the computational design. This software allows an analysis of a set of parameters, or genes, seeking to fulfil multiple objectives, in an attempt to generate a series of optimized solutions between the maximum of each of the objectives introduced. In this case, it seeks not only to minimize weight and deformation but also the amplitudes, due to the poor capacity of the ceramic material to produce elements with high amplitude values. The results of this optimization are presented through a cloud of points, and from this it was possible to identify 3 type solutions, a hexagonal base solution (A), a triangular base solution (B) and quadrangular base solution (C) for later comparison.

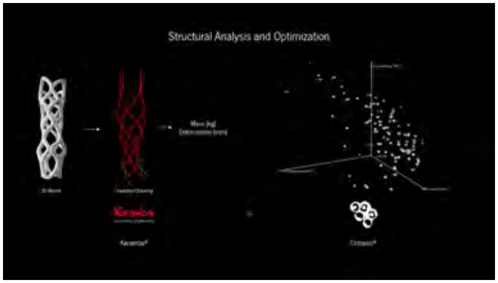

Figure 4
Structural Analysis and Optimization using Karamba3D and Octopus

24 FINAL PROTOTYPE DEFINITION

For the selection of the prototype to be produced, two parameters were considered. The first one, more objective, based on the results of the structural behaviour of each of the columns and a second, more subjective, concerning the design of the prototype. The process of defining architectural objects always implies the control and definition of the morphology and proportions of these objects, so this analysis also weighed in the selection of the prototype.

The selection began with a comparison of the structural results of the three columns, which immediately led to the removal of solution B from the options. With the choice to be divided between the other two solutions, the option ended up with solution A. Among the three hypotheses, this one presents not only a better deformation and axial strain value, but also a design that formally interested us to experiment because it is the one that presents more similarities to the trunk of the Ficus plant.

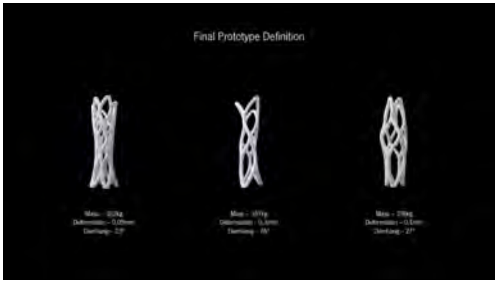

Figure 5
Final Prototype Definition

3 PREPARATION AND PRODUCTION OF THE PROTOTYPE

When dealing with additive manufacturing processes it is important to realize the process behind the method and in this sense, it is important to realize that the language of the digital design and the language that the printer reads are different. Therefore, it is necessary to translate the object language into the printer language, called g-code. There are several software capable of this translation, however it was chosen to execute it through Grasshopper®, allowing not only a customization of the code, but also developing it on the same platform as the project, approximating the stages of design and construction, which are generally autonomous and distinct (Carpo, 2013).

31 FIRST TESTS AND PROBLEMS

The objective of the first tests of manufacture was to define the initial parameters of manufacture, with respect to the height and the thickness of the layer, so different combinations were explored, being established in the end that would be used 3mm of thickness and 1,5mm of height , to a scale of 1:5, which could then be adapted based on the scale wanted to manufacture. These manufacture tests also allowed to check already some problems in the manufacturing process, namely the fact that the extruder tip dragged ceramic material during its course, creating several imperfections in the prototype.

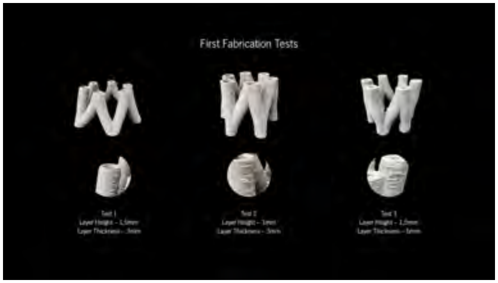

Figure 6
First Tests and Problems

32 OPTIMIZATION OF THE FABRICATION PROCESS

To try to prevent the extruder tip from dragging material along the path defining the prototype's design, a simple 5 mm rise in the Z axis was generated in the print code whenever a certain part of the print path was completed. Thus, at such times, the extruder tip stopped extruding material, moved up in the Z axis, moved to the next design location, dropped and continued the extrusion and so on until the manufacturing process was completed. With these changes implemented, results that showed good levels of quality began to emerge.

Figure 7
Optimization of the Fabrication Process

33 FINAL PROTOTYPE FABRICATION

There is, with this research, the ambition to manufacture a full-scale prototype, and in this context, we can have two approaches with regard to its production method. A first approach that deals with printers with small volumes, for the production of structural components. These components are divided into parts, through section plans that cut the geometry, and a second approach, where these limitations are non-existent, thus making possible a continuous manufacturing of the prototype.

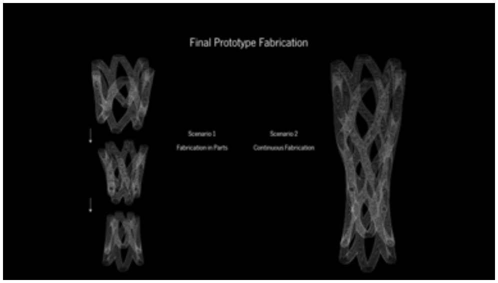

Figure 8
Final Prototype Fabrication

331 FABRICATION IN PARTS

Starting with the first scenario, the complications in assembling the parts were already evident, due to another characteristic of the ceramic material, the question of the retraction, which begins at the drying stage and stabilizes after the firing process, affecting the final dimensions of the prototype. In this case, this meant that the connections between the parts would not work. Therefore, the solution was to implement strategic compensations on the tops of each part, so that with the established retraction the pieces could fit together. Therefore, it was necessary to know the retraction indexes of each part.

Through a comparison of the dimensions of the digital drawing, which we see in red, and the printed pieces, which we see in white, it was found that the tops of the pieces retracted 15% and the bases retracted 8%. These differences are due to the fact that the bases are resting on a refractory plate, which due to its texture causes friction and limits the retraction of the prototype, as well as due to the self-weight of the parts.

Knowing the percentage of shrinkage of each part it was possible to calculate that the top of part 1 would have to be increased by 6.5mm and the top of part 2 would have to be increased by 11.6mm so that with the retraction the dimensions of the connections allowed the fit between them.

With this, it became possible to interconnect the parts, so that mechanical fittings were later developed to fix them. These fittings are simple tubular profiles, also produced in 3D printing, in this case in polymer material, and are placed inside the ribs, as it was intended to minimize their presence in the design of the column. Its lateral flap tries to avoid contact between two ceramic surfaces, avoiding the risk of parts cracking or even breaking in the moments of connection.

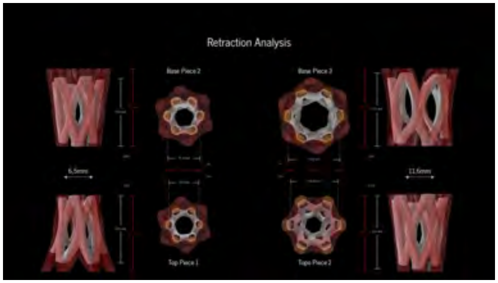

Figure 9
Retraction Analysis

332 CONTINUOUS FABRICATION

In the second scenario, the issue of shrinkage does not have the same degree of importance as in the first, because the prototype is developed continuously, however if we are faced with a situation where the printed prototype needs to have dimensions such as those of digital drawing, we must take into consideration the retraction values.

As it was intended to compare the results between the two methods, we analysed the retraction values of this scenario also. In this case, the retraction at the top was 15%, just like the other scenario, and the difference was at the base, which fell to 11%. However, the most unexpected results were the rates of retraction in height, which presented even higher values.

In this case, the prototype printed in parts retracted 21% and the continuous printing prototype retracted 17%. At the start it was thought that the continuous printing prototype would exhibit higher retraction values because it was a larger and heavier piece, so it was thought that these factors would accentuate the retraction, but the opposite was true. What is thought to be the origin of this result is the area that is exposed to the air, the first scenario, printed in smaller pieces has the inner volume more easily exposed to the air, however in the second scenario, due to the its height, this contact is smaller, affecting the way the retraction process acts on the prototype.

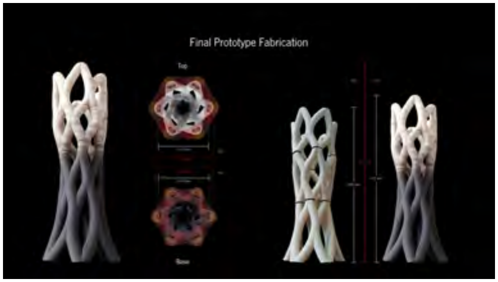

Figure 10
Fabrication
Scenarios
Comparison

4 FINAL CONSIDERATIONS

The association of additive manufacturing with ceramic material allows to explore new ideas and objectives in the built environment, however it is necessary to take into account certain considerations. Namely, its difficulty in producing amplitudes higher than 30º and especially, we need to consider the retraction values, since they have serious repercussions on the final result of the prototype. Finally, the integration of computational and parametric design in architecture is an added value for the work process, because it is a tool that not only helps the design process, but also streamlines the whole construction process of a given project.

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Guiding Instability

A craft-based approach for modular 3D clay printed masonry screen units

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As the field of 3D printing technologies expand, complex materials that require a deeper engagement, due to their more unstable properties, are of increasing interest. Cementitious composites, clays and other ceramic materials are of particular relevance: their potential for fast large-scale fabrication and local availability position these technologies at the forefront of expansion for 3D printing. Despite the extensive benefits inherent to clays, their irregularities and the largely unpredictable deviations that occur when printing from a digital model, currently limit design and architectural-scale applications. However, these deformations could conversely be harnessed as design generators, opening up avenues for both aesthetic and functional exploration. The paper presents an investigation into the inherent material instabilities of the clay 3D printing process for the development of an architectural masonry facade system. Through an iterative process based in craft, a new capacity for material expression and authenticity beyond previous manufacturing capabilities can become actualized.

Keywords: *3D printing, digital craft, clay, material computation, uncertainty, hybrid fabrication*

INTRODUCTION

The 4th industrial revolution promises the distribution of manufacturing and the re-conceptualization of the means of production. 3D printing processes are part of this shift. These technologies are utilized with the intent for accurate and precise reproductions of complex geometries and as such, most research has focused on achieving predictable and “stable 3D deposition shapes” (Gibson, Rosen, and Stucker 2015). For this purpose, materials with relative low cost and predictable behaviour, like photopolymer resins or dimensionally stable thermoplastics have been ideal (Dizon et al. 2018). However, as the spectrum of 3D printing technologies continues to expand, new applications and materials are being explored that more directly engage these complex properties and question the paradigm of control and imposition of form in the applications of 3D printing technologies. Furthermore, despite this paradigm for precision, inherent to many 3D printing processes - notably fused filament fabrication (FFF) processes that rely on material build up through directional layering - are material anisotropies resulting from the printing process which introduce undesired deviations in the final print (Dizon et al. 2018). While extensive literature exists to understand and mitigate some of these irregularities to produce reliable and repeatable parts within narrow tolerance margins, these material instabilities can conversely be engaged to open up new and unique design territories. For instance, stress concentrations as well as micro and macroscopic anisotropies have been explored as drivers of 4D behaviour (Correa Zuluaga 2015; Tibbits 2017; Momeni et al. 2017) while tool path orientation in FFF has been used for the development of functionally differentiated (Oxman 2011) or structural optimized components (Chapiro 2016; Malek 2017; Compton and Lewis 2014). Key within them, is the engagement of materials that may have been previously overlooked for 3D printing processes due to their inherent material irregularities, instabilities or non-linear behaviour. Clay - due to its low cost, local material availability, and rich craft tradition -is one of these materials of interest for FFF processes.

Clay is widely used in both vernacular construction as well as high tech applications: traditional ceramic crafts have developed specialized methods that harnesses and celebrates the variability of each piece, while industrial ceramic manufacturing have developed precise processes and recipes (e.g. dies and moulds) in order to mass-produce standardized, repetitive pieces of high dimensional precision. Yet, despite its ubiquity, clay is seldom found in 3D printing processes for architectural applications due to its inherent material irregularities, instabilities and non-linear behaviour while wet.

3D printing clay via FFF presents a multitude of internal and external challenges, including but not limited to, clay viscosity, slumping, ambient environmental conditions, and movement of the print-head, each of them contributing to unpredictable deformations and deviations in the resulting print (Gursoy 2018). Consequently, it is difficult to predict and simulate all the variables and their interactions within a digital model (Gursoy 2018; Rosenwasser, Mantell, and Sabin 2017). Realtime adjustment to error is also difficult as multiple parameters, such as uneven drying or sagging due to self weight can cause internal stresses that will still affect the final outcome post-print. Several architectural scale projects have been developed using clay FFF processes (Peters 2014; BAT 2017), which operate under a "clear mandate of tight construction tolerances" (Seibold et al. 2017). In other words, these projects have optimized workflows to minimize potential deviations and consider the irregularities of clay as obstacles for geometry fidelity.

However, recently this error-prone predisposition of clay FFF processes has been investigated by designers with the explicit aim to express emergent aesthetics through its composition variability, and to reveal emergent effects created by the printing process (Gursoy 2018; van Herpt and van Broekhoven 2015; Rael and Fratello 2018). These experiments explore new material aesthetics and re-interpret artisanal methods from handmade ceramics where a deep understanding and learned knowledge of material and technique inform the final outcome (Kolarekic 2008). However, literature is limited in providing methods to achieve these results or examples that identify the architectural potential of these instabilities at the larger scale needed for design and building construction. Furthermore, existing research for architectural scale projects that readily engage the expressive potential of instability in clay FFF processes are currently limited to panel type screen assemblies (Friedman, Kim, and Mesa 2010; Rosenwasser, Mantell, and Sabin 2017).

In this context, the presented paper demonstrates a clay FFF method that harnesses the material computation capacity of clay and the unpredictable deviations between digital input and final artefact as design drivers for an architectural masonry façade system. Through a reciprocal, digital to analogue, experimentative and iterative design process based in craft, it is demonstrated that the instrumentalization of material instabilities can be used to achieve desired functional performance and material expression.

Figure 1
Masonry screen showing aperture opening from right to left

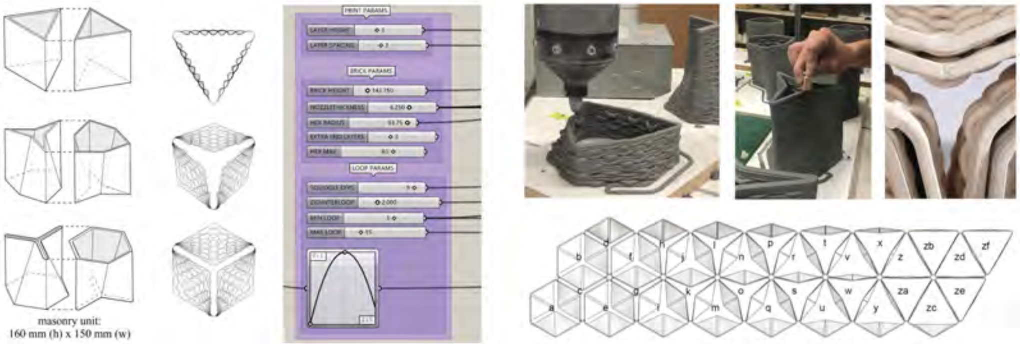


Figure 2
A) Interlocking single layer shell masonry units. B) toolpaths generated from grasshopper. C) printing and stamping process. D) general assembly plan

METHODOLOGY

Using paste extrusion deposition, an interlocking screen system was developed that parametrically modulates light while testing the plastic deformation properties of clay for formal expression and ornamentation through the addition of loop forms. The printed test wall consists of 32 unique interlocking masonry units, stacked four rows high, measuring 1000mm x 300mm x 175mm (Figure 1).

The prototype was developed using the Potterbot Scara XLS-2, with a 3600 ml extruder. A commercially available earthenware clay product, containing a 50:50 talc to ball clay ratio, was used for its high plasticity and drying performance. The clay was prepared, prior to printing, by increasing the moisture content of bagged clay (10 oz per 25lb of clay). The pieces were printed onto melamine boards to minimize moisture absorption and adhesion to the printing bed. A geometric strategy of manipulating single layer shells was adopted for the masonry unit design in order to accommodate a continuous spiral toolpath, and an integrated digital parametric model was developed using Rhinoceros and Grasshopper, which allowed for precise manipulation of geometric variables (Figure 2). The digital model was then translated into G-code toolpaths using Simplify3D, while on-the-fly adjustments of extrusion speed and flow rate, using the printer interface, accounted for slight discrepancies in material consistency.

To better understand the material behaviour of the clay filament, an iterative design approach to the development of the masonry unit was implemented. Each iteration tested deviations (e.g., slumping, sagging, and collapsing) between a prescribed digital model and the resulting form. The results were evaluated based on their potential to enrich the printed masonry unit as a design feature. Certain variables were kept constant such as temperature, clay "wetness" (moisture content), extrusion speed, and extrusion layer height, while other variables were further modified such as nozzle diameter, orientation of print, slope, height, size and geometry of the masonry unit.

Documentation of the masonry units became integral to the development of the design and were used as references to understand the deviations found between the printed clay masonry unit and digital model. Photographs of the bone-dry masonry units were used to compare the varying printing parameters. The masonry units, while leather-hard, were sliced to understand how the changing parameters affected the interlocking fit. Digitally scanning key prints provided additional insight to the modes of deviation between digital model to printed masonry unit (Figure 3).

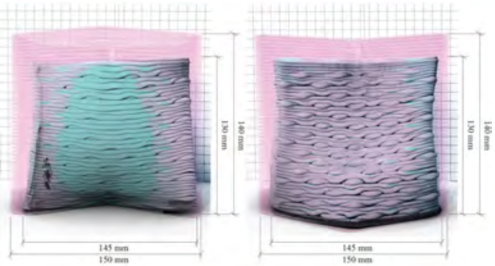


Figure 3
Digital model (pink) vs 3D scan of bone-dry printed piece (blue)

The material computation capacity of clay and its effect on the final form - notably the overall shape deformation due to self-weight (also referred to as slump) and the "loops" that emerged from unsupported clay bead overhangs - became the primary focus for the design team. Once these key design drivers were determined, the digital model's parameters were calibrated to investigate the interdependence of, and potential design space, that these material properties could facilitate in the physical form.

RESULTS
The final digital model and corresponding toolpaths were informed by specific parameter values after extensive testing and calibration as there was no way to predict the natural tendencies and reactions of clay a-priori. An iterative method of experimentation between analog parameters (nozzle diameter, slump deformation), and digital parameters (tool path, extrusion rate and movement speed) allowed for the final objects to emerge.

Slump
The malleability of the clay was an important factor in understanding several properties of the masonry unit. In addition to maintaining a consistent extrusion rate, keeping the viscosity of the clay consistent allowed for the controlled testing of global deformation due to self weight, i.e. slumping or warping. Due to the plasticity of the clay and the slanted angles of the exterior surfaces of the masonry unit, each brick had a tendency to globally deform and slump. A paradigm of zero tolerances and perfect fitting systems would not have been suitable here. This deformation could have been catastrophic if each unit was to perfectly match the digital model's assembly parameters (Figure 4). However, printing the matching interlocking masonry unit upside-down, keeping clay viscosity and environmental conditions consistent, computed a matching fit. Flipping alternating masonry units also affected the sag direction of the loops, creating distinct texture characteristics for each side of the wall (Figure 5).

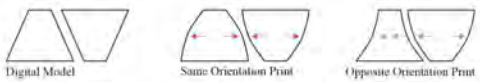


Figure 4
Effect of print orientation on slumping

Figure 5
Slumping match when print orientation is inverted

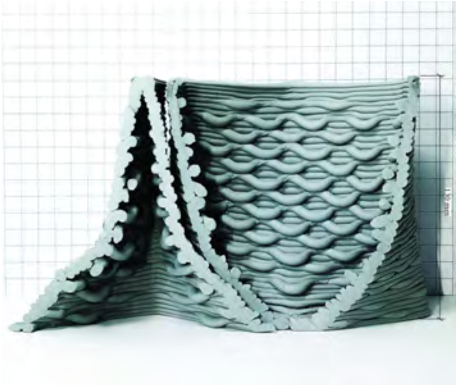
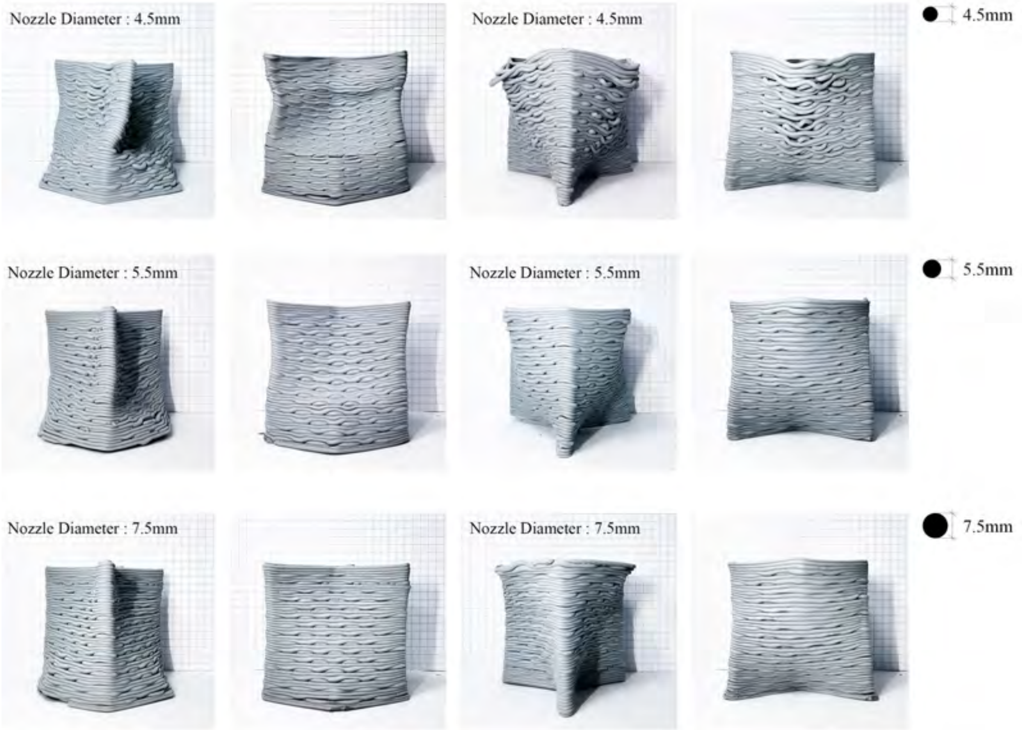


Figure 6
Nozzle diameter size testing for overall form, surface pattern quality and consistency.



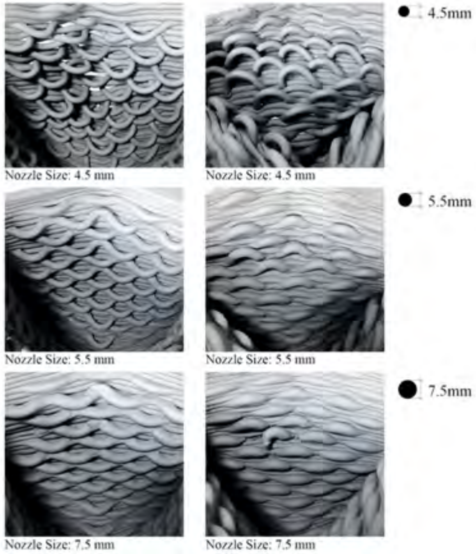


Figure 7
Tests of nozzle diameter in relation to loop pattern creation

Nozzle Diameter

The layer height and nozzle diameter used for the extrusion of the clay filament affected the surface quality, wall thickness, inter-layer bonding and general structural stability of the overall print, therefore multiple diameters needed to be tested in order to determine a suitable size. If the nozzle diameter was too narrow, the lower structural capacity of the thin walls combined with the self weight of the masonry unit, caused the piece to excessively slump and buckle until failure. While if it was too wide, geometric definition was reduced, compromising subtle features of the masonry system (Figure 6). Additionally, the nozzle diameter altered the effectiveness of the loops in terms of size and strength. For example, loops created with wider nozzle diameters sagged less and were stiffer, causing loops to tear in the curvature points. Alternatively, loops extruded from narrower nozzles sagged more and thus increased in size, but the greater overall slumping of the masonry unit resulted in poor adhesion between layers (Figure 7).

Digital Tool Path

Throughout the iterative testing of physical parameters, a continuous and parallel calibration of the digital tool path was necessary to adjust to the natural reactions of clay. As the loops were designed as unsupported cantilevers, the nozzle diameter and viscosity of the clay ultimately determined the length and shape of the loop's final digital tool path. Different nozzle diameters affected the flexibility and weight of the extruded clay bead, consequently the same digital tool path resulted in noticeably different loop appearances and geometries. Therefore, a careful calibration of the digital model was required. For instance, the configuration of the loop pattern required various test prints in order to achieve the desired surface quality (Figure 8). The final loop configuration consisted of loops separated by three extrusion layers in a staggered pattern to prevent drapage of loops on top of each other. Additionally, the chosen configuration seemed to provide additional interlayer adhesion by allowing the loops to form additional contact points to the layers below.

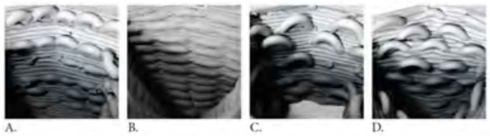


Figure 8
Loop configuration tests : A) loop layer every 4 layers. B) loop layer every 2 layers. C) staggered loops every 4 layers D) staggered loops every 3 layers.

Due to the malleable nature of the clay while printing, the movement and speed of the print head had unexpected effects on the clay wall. The toolpath action to print loops, combined with the self-weight of the clay bead, incrementally pulled the clay wall inward and eventually resulted in print failure due to the misalignment of layers. To correct this deviation, a small counter-loop action (a small cantilever in the opposite side of the wall) was added into the toolpath after each loop to pull the wall back in alignment (Figure 9). Various testing of counter-loop depths were taken place to evaluate the appropriate size. (Figure 10) If the counter-loop was too small, the movement was not sufficient to correct the initial pull and caused layers to misalign. Conversely, if the

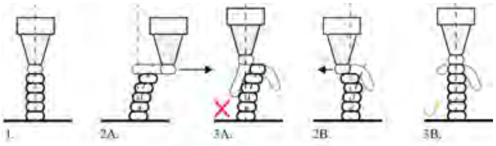


Figure 9
Counter-loop mechanism: A) toolpath aligned with wall. 2A) loop action causes printhead to pull wall. 3A) wall is no longer aligned with toolpath. 2B) small counter-loop action pulls wall back. 3B) wall is re-aligned with toolpath

counter-loop was too deep, the resulting excess clay build-up on the surface and corner of the masonry unit compromised the fit of the interlocking system.

DISCUSSION

Working with clay in a multi-component assembly offered a complex set of design challenges. The FFF process is highly susceptible to irregularities that were easily compounded in a multi-component assembly. The development of the presented masonry units required a direct engagement and an openness to experimentation with both the material qualities and the fabrication process. This open-ended process, supported by consistent documentation and controlled through an integrated parametric model, created a framework that allowed for both the systematic calibration of parameters and the emergence of unexpected findings.

Flipping the print orientation provided a direct method of resolving the geometric compatibility within the interlocking system; however, it also offered a different manifestation of the loops depending on print orientation that contributed an additional layer of complexity to the material aesthetics of the masonry assembly. While this technique enables interlocking designs to meet fit tolerances, it also suggests there is more investigation needed in exploring other applications and design potentials of the material computation capacity of wet clay. Similarly, the loop's capacity to increase interlayer adhesion provides opportunities for further investigation into the aesthetic, formal, and structural potentials of different loop configurations. By strategically layering loops, different wall thicknesses, sectional variations, and textures could be achieved, and could also present an alternative method to creating thick walls. More testing is needed to fully understand the impact of these layered loop structures on durability and overall slumping.

Imagined at a larger scale, a customizable architectural masonry screen assembly with parametrically controlled apertures may be able to respond to a number of design criteria such as solar control, airflow, visibility gradients, etc. The printed test section of the masonry screen, presented here, demonstrated the feasibility of the system, both in terms of multi-unit assembly as well as its architectural potential, to modulate light and provide visual complexity (Figure 11). However, building a larger section of the wall assembly would be necessary to fully understand the requirements for implementation in practice under various environmental conditions.

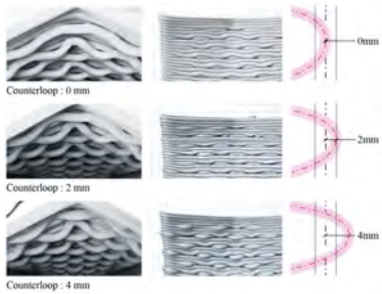


Figure 10
Counter-loop depth tests showing effect on layer slippage and surface quality

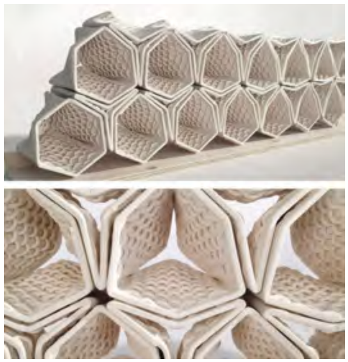


Figure 11
Printed test section of the masonry screen assembly

CONCLUSION

Redefining what is made and how it is made sits at the forefront of the 4th industrial revolution and is a core question within the architectural practice. With the embrace of heterogeneity , there are opportunities for unexplored material properties to emerge as design generators of new functional characteristics rather than obstacles preventing reproductions of imposed platonic forms. Instead it offers opportunities to enrich the process and outcome. For architectural design, this opens up new avenues for local adaptation, contemporary ornamentation and shared authorship - where incorporating a mediated variation adds another layer of aesthetic complexity in the final form. While in practice, the potential given by guiding instabilities of clay FFF processes expands the applications of large scale construction and rapid prototyping, due to its low cost, local material sourcing (clay, adobe, biocomposites, etc), workability of material and ease of post processing.

Through an iterative process based on craft, a new capacity for material expression and authenticity beyond previous manufacturing capabilities can become actualized.The precision of new manufacturing methods like 3D printing combined with an inquisitive engagement of material processes can result in hybrid processes of design and making. Perhaps the 4th industrial revolution is a challenge of fusing territories as it is a challenge of mediation, the unique and the ordinary, the mass produced and the vernacular, the designed and the emergent.

Acknowledgements

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Free-form Ceramic Vault System

Taking ceramic additive manufacturing to real scale

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The use of Additive Manufacturing (AM) for the production of architectural components has more and more examples attesting the possibilities and the advantages of its application. At the same time we seen a fast grow of the usage of ceramic materials to produce fully customised architectural components using Layer Deposition Modelling (LDM) [1] techniques. However, the use of this material, as paste, leads to a series of constraints relative to its behaviour when in the viscous state, but also in the drying and firing stages. Thus, when ceramic dries, the retraction effects may be a barrier to the regular use of this material to build future architectural systems. In this sense, it is important to study the material behaviour and know how to control and use it as a primary construction material. To do that we present the challenges and outcomes of project Hexashade, a ceramic vault shading system prototype whose geometry and internal structure is defined according to the solar incidence. This paper explain how we expect to build a real scale self-supporting prototype.

Keywords: *Ceramic 3D printing, Additive Manufacturing, Vaulting Systems, Parametric Design, Performative Design*

1. INTRODUCTION

Digital manufacturing processes allows a faster and more precise production of complex architectural components, expanding considerably the architect role and the possibilities of how and what is possible to build. The merge of digital design tools and additive manufacturing technologies enable the execution of entirely customised systems, developed to specific contexts, answering with balance and adapted solutions.

The research described in this paper follows a previous work named 3D Printed Ceramic Vault Shading Systems (Carvalho et al.) that was also developed in the context of the Advanced Ceramics R&D Lab (ACLab) projects. Based in the Design Institute of Guimarães, the laboratory intend to explorar the applicability of AM techniques such as LDM of ceramics, on architectural design and production processes.

The study focused on the development of a self-supporting domed roofing system, formed by customised hexagonal blocks in which the size of their openings and internal structure configuration allow to control the solar incidence. During this study a 1/2 scale prototype (Figure 1) of a part of the origi-

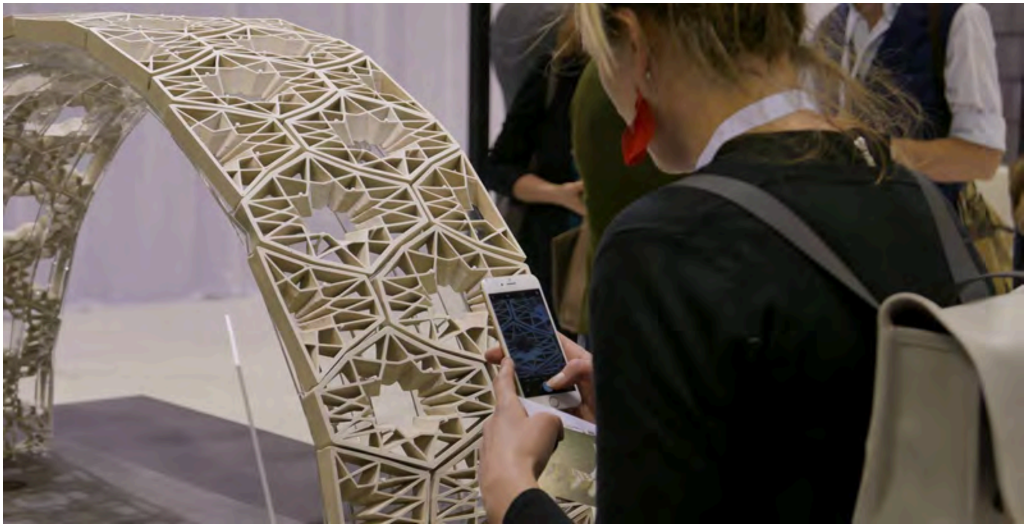


Figure 1
Ceramic Vault
Shading System
Prototype in
exhibition.

nal structure was produced. In this sense, the present paper aims to synthesize the problems encountered during the various phases of this study and to point out methods and solutions for their mitigation.

2. CONTEXT

The previously described research resulted in the enunciation of problems that prevented the manufacture and assembly of a full-scale prototype as originally planned (Figure 2 - right). Instead of this formalization, the study resulted in a reduced-scale prototype with no self-supporting capability, requiring an acrylic substructure to support it, and listing a series of formal and material issues that made it impossible to produce a full-scale model. Of these problems, four are of particular importance: (a) the aforementioned absence of self-supporting capacity; (b) the connections between components that did not worked properly due to non-correspondence between juxtaposed faces; (c) the retraction of the parts during the drying and firing phases caused a mismatch between the physical models and the digital models; (d) the punctual surface cracking due to non-uniform shrinkage which drastically reduced the load capacity of the structural elements.

2.1. Lack of self-supporting capacity

The lack of self-supporting capacity of the shading system assembly is perhaps the main obstacle to the production and construction of a full-scale model. Of the small scale models carried out so far none of them have the capacity to support their own weight without the aid of another element, contrary to the initial objective of the project.

Contributing to this fact will certainly be the dimension of the height of the pieces wall (arch thickness) which does not allow a stable support, either for the part or for the set. In addition to being reduced, there is still the problem that this thickness is constant throughout the arch, so that the elements that are on high stress have exactly the same structural capacity and weight as those that have to respond to lower requests, with no correspondence between structural request of the set and the response capacity of the elements.

2.2. Deficient connection between components

The deficient connections between components result from the natural deformations of the ceramic paste during the later stages of manufacture, dewatering and firing. This characteristic is natural in viscous materials that incorporate water in its composition and tends to cause deformations in the constructed elements by the reduction of volume, be it general or punctual, in the latter case determined by the existence of complex geometries.

Also, the friction between the printing bed (refractory plate) and the produced part (first layer), which is beneficial during printing, is bad in the later stage by not allowing the free movement of the component at the base, causing the loss of moisture to result in more deformations, in this case unpredictable. During the execution of the test models, various types of connection between the ceramic elements were realized, from fittings formed in the part itself, to the execution of external connecting pieces made from other materials, namely in PLA by FFF. None of the elements tested revealed the strength needed to ensure the integrity of the system.

2.3. Retraction of ceramic material

From the retraction of the ceramic material in addition to the aforementioned deformations on the surface of the parts, there is also a general mismatch between the scales of the digital and physical models. One of the characteristics evidenced during the execution of the reduced scale tests was that the retraction of the ceramic paste is not regular, varying throughout the piece. It was noted that the retraction value of ceramic pieces has large oscillations in the various directions, these variations being directly related to the geometry and quantity of material (mass) in each direction.

There is a large discrepancy between the retraction values in the two main directions of the executed pieces (X and Y), and the only difference between them is the extension of the segments that form them. It is observed that the smaller the dimension of the piece in a certain direction (smaller quantity of material) the greater the value of its retraction, since to resist the efforts of contraction of the ceramic will be less volume of material.

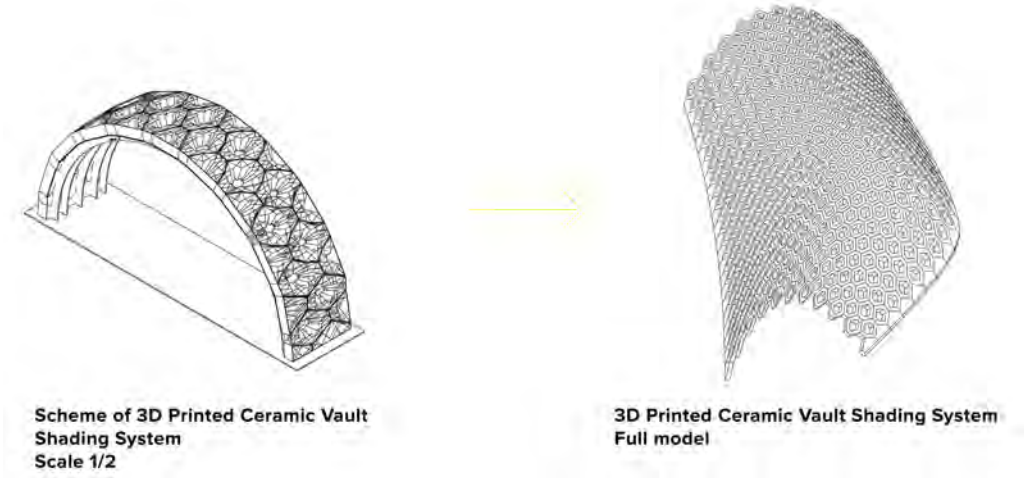


Figure 2
Hexashade 1/2 scale prototype (left) and the complete shading system (right).

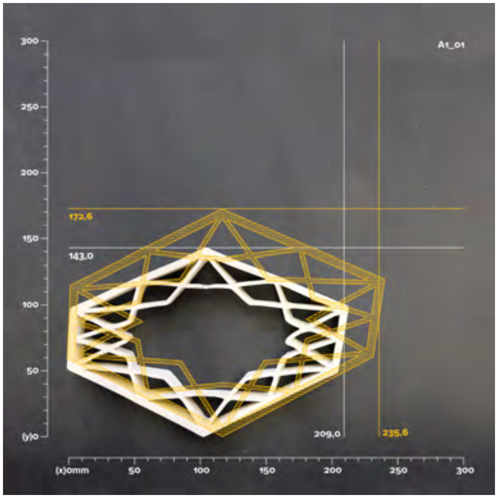


Figure 3
Retraction analysis. Comparison between the digital and physical model.

2.4. Surface cracks

During the execution of the first printing tests it was recurrent the appearance of breaks and cracks in the walls of the printed elements. Its origin is related to several factors that later began to be considered for the execution of the parts, resulting in modifications of the configurations of the entire production process.

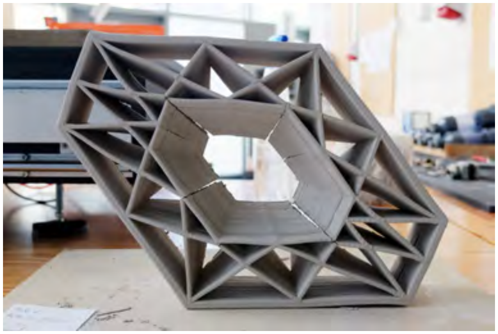


Figure 4
Surface cracks. Real-scale model.

From these we highlight (a) the friction that exists between the printing base and the base of the part, which can result in breaks when the resistance exerted to the movement is higher than the resistance limit of the material, (b) the loss of water under uncontrolled environmental conditions, and (c) complex geometries, which may be incompatible with the mechanical configurations of the equipment or with the material, and which may lead to non-uniform distribution of material by the element, causing various retraction values.

In Figure 4 it is noticed that the breaks follow a pattern and, in this case, concentrate on the encounters between different extrusion paths, namely in the connections between the internal structure and the internal walls that conform the opening of the piece, pointing out ways to its possible elimination.

3. METHODOLOGY

In order to mitigate all these problems, a careful analysis of the variables under study was made, as well as the cross-referencing of data inferred from other projects developed at the Advanced Ceramics R&D Lab, such as the Wave Wall [2], and external examples of design solutions that presented good results, such as the 3D Printed Shelter from ELStudio [3].

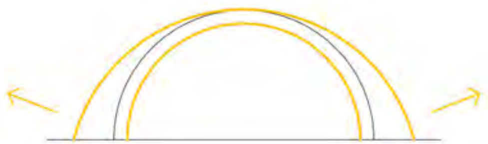
For the execution of these changes the object of analysis is divided into two moments. Firstly, as a whole (set of all the pieces), for the resolution of the lack of self-supporting capacity and connection between elements, and in a second, in which each piece is individually treated, for the deformation that compensates the retraction effects.

3.1. Lack of self-supporting capacity

In order to solve the first problem, the lack of self-supporting capacity, it was thought a formal revision of the whole set, resulting in a redistribution of mass by the pieces based on the relative position of each component in the set. That is, a generalized increase in the dimension perpendicular to the arch in each of the pieces, decreasing in value from the base to the top.

In the previous proposal all the blocks had the same height and the same number of layers not considering each position in the set. In the context of this proposal the height will be variable, with more height in the lower position parts, meaning heavier and stronger areas at the base, making this is a more optimised solution for the structural needs of each part of the arch (dome).

Figure 5
Mass redistribution scheme.



In order to be able to print a block with variable height it was decided to distribute the number of printing layers evenly on each block. As shown in Figure 6, in the areas of smaller height the spacing between the extrusion paths is smaller than in the higher parts. In order to maintain control of the extruded material quantity, trying to keep a proportional relation between less layer spacing with less material deposition (preventing excessive shedding), it is proposed to reduce the speed of the spindle (extruder) in these sectors, maintaining the travel speed constant.

Figure 6
Material extrusion scheme.

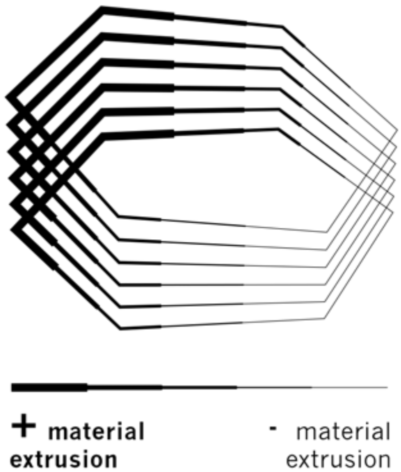


Figure 7
Interlocking system scheme. Smooth deformations that block the movement of the parts.

The implementation of this process implied the update of the previous code, developed in the ACLab [6], including the possibility of customization of the speed parameters (displacement of the extrusion nozzle in X, Y, Z and the number of revolutions of the extruder spindle) and its translation into G-Code speed parameters.

In addition to the customisation of G-code it is also necessary to reconfigure the printer controller, in order to modify the pre-established relationship between travel and extrusion speeds. At the same time, thinner blocks near the keystone, with less structural request, will be conformed by fewer print layers.

3.2. Connections between components

The connections between the various components of the assembly that made it impossible to assemble correctly due to the non-correspondence between faces, which also meant that the assembly did not have the capacity to withstand load requests, requires a new formal change, characterized by the abandonment of connections made by complex geometries and the application of light surface deformations, only in order to counteract the direction perpendicular to the loads, preventing the displacement of the blocks from the original position, locking the assembly.

This change, represented in Figure 7, similar to the one used in the investigation of Matthias Rippmann and Philippe Block (Rippmann et al.) is characterized by the implementation of slight deformations on the side faces of the blocks in opposite directions, leading to that when the assembly is complete it is impossible to detach any of the parts, making it a reciprocal and solid structure that does not require additional support elements.

3.3. Retraction issues

In order to solve problems related to retraction, has been implemented a computational model that analyses each of the elements and makes the necessary formal modifications, so that in the end, taking into account the characteristics of the ceramic paste (retraction values), the final model is an exact physical representation of the digital one in which it is based.

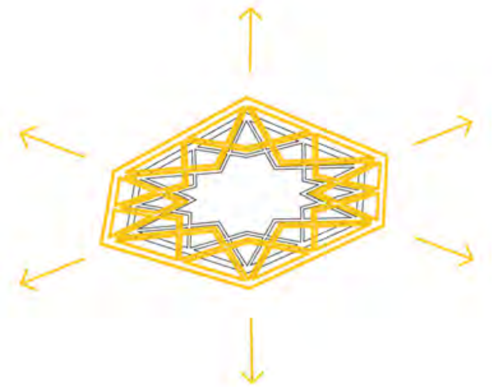


Figure 8
Computational model scheme. Deformation of the initial digital model taking into account the retraction values.

This reverse engineering exercise simulates the LDM process that considers the formal configuration of the objects after occurrence of the retraction effects, that is, scaling up the digital model to when it retracts, became equal to the original digital one. The shape changes introduced by the computational model encompass three moments, the base shape control polygon (modification of the X and Y axes), the top shape control polygon (modification of the X and Y axes), and distance between the two previous polygons (shape change in the Z axis).

3.4. Superficial cracks

The issue of surface breaks is not only explained by the normal behavior of the material over time (retraction), but is more difficult to prevent or avoid. The surface breaks happen at particular moments, where the tensional stress in the material exceeds the maximum resistance of the same, leading to the collapse of the connections.

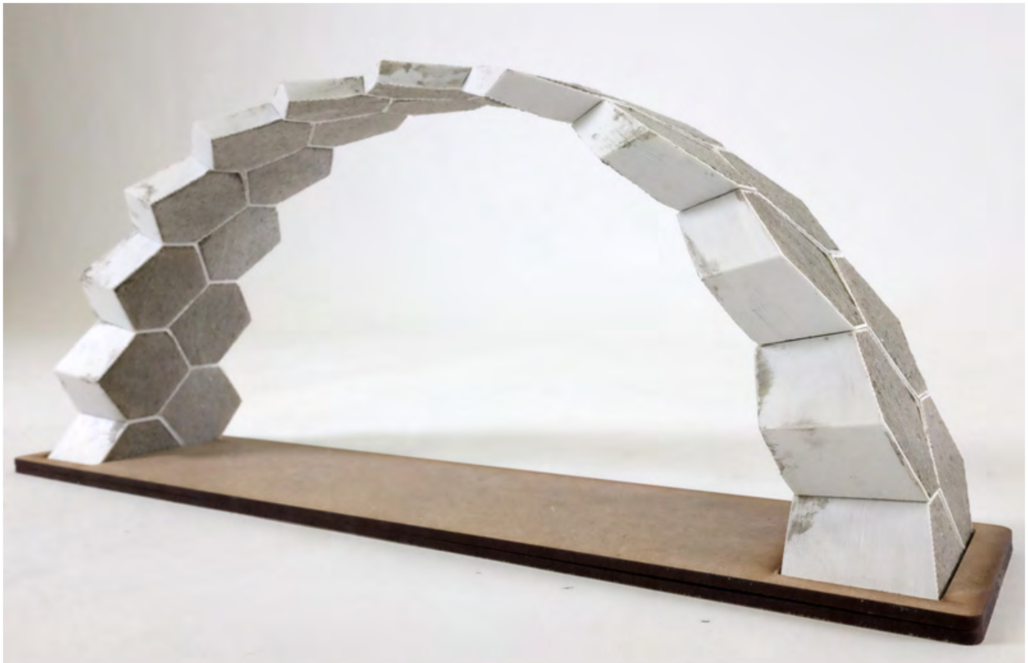
To avoid breakage, the inclusion of additives in the composition of the ceramic paste, namely glass fiber and sawdust was tested, giving the pulp greater resistance to tensile stresses during the dehydration phase. The inclusion of additives in the ceramic paste, while providing the blend with more tensile strength at the moment it is retracting, lowering the water levels, also has implications for the final performance of the element, insofar as it changes its composition compared to an element solely formed by ceramic. In addition to changing the chemical properties of the material and consequently its response to stresses, the addition of some types of material to the ceramic paste, namely fibreglass (Figure 9) considerably changes the finish of the piece, giving it an appearance rough finish with many irregularities.

To prevent the occurrence of breaks along the surface of the elements produced, in addition to having control over the temperature and humidity of the space where the parts will remain to dehydrate, there should be control over the geometry of the segments, introducing variables such as thickness and height of the layer, and on the print paths, defining the most suitable deposition sequence so that the successive passages do not weaken the part.

Figure 9
Mixture of ceramic with fibreglass.

In addition to the breaks that occur during the dehydration phase, sometimes there are breaks during the cooking phase (in a controlled environment). To avoid such breakages, changes to the cooking programs will be made by modifying the heating curves and consequently the reaction of the material to the heat. We will be particularly concerned with the ce-

Figure 10
Small scale model with the implemented changes.



ramic expansion phase (approximately 600ºC) and with the vitrification phase (approximately 1250ºC), trying to smooth the effects of the chemical alterations.

4. RESULTS

The modifications described above mainly result in formal changes in the components, assuming the stabilization of the configurations of the material, maintaining the composition and the amount of water present in the ceramic paste.

Since our goal was to reach a self-supporting structure, the first iteration to the previously explored methodology would have to be in relation to the capacity of the structure to support itself without external elements, something that is achieved by the redistribution of the mass inside the assembly that conforms the structure, although there is place to a considerable formal change. Here, a logic of agreement between loading requests and the volume of material in each component was applied.

In addition to the need to reformulate the mass distribution in the set, it was necessary to revert the effects of ceramic retraction. Here the results obtained are not characterized by the abolition of such material characteristic but, as mentioned above, by the analysis of the retraction values and subsequent compensation, causing the produced geometry to be a controlled deformation of the initial geometry that, in the end of the entire production process, gets much closer to its digital version.

In the connections between pieces, once only soft surface deformations have been used, there is a good correspondence between juxtaposed faces of different blocks, allowing good fittings. Although these deformations are relatively small, in some cases they cause the increase of vertical inclination, and consequently increase the deformations on the surface. These deformations can be corrected during the phase in which the block is dry, by the regularization of the surface by abrasion tools.

Related to the use of additives to help stabilise the ceramic material while it is still not resistant, the results show that despite helping to compensate the lack of response of the ceramic to tensile and flex stresses during the drying process, this addition causes that, by the method how the production is made, the fibbers sometimes cause defects in the surface finish.

5. DISCUSSION

The problems pointed out at the beginning of this paper may prevent the execution of some projects in which, as in the case of Hexashade, its structural integrity is dependent on the formal correspondence between the juxtaposed faces of the elements that compose the set, or the co-correspondence between the model produced and the digital model.

In this sense, the presented methods constitute a set of actions that we consider as possibilities so that there is correspondence between the digital model, totally developed in computer environment and its material formalisation produced in ceramics through the LDM technology. These methods aim to control the behaviour of the ceramic paste during the moments after the production, predicting and counteracting the deformations that it may suffer, according to the characteristics of the material to be used in the production.

AM in viscous materials such as ceramic or concrete are quite challenging in that they allow a very close connection between tradition and innovation, incorporating formal and material parameters not yet explored.

Assuming this as a continuous work, with further studies and new tests to be done, we point as the next step the use of superplasticiser additives that help to control the plasticity of the ceramic material while the amount of water present in the pulp is reduced, a situation that, pervisibly, will result in less significant deformations and easier to control.

ACKNOWLEDGMENTS

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Design Method for Optimized Infills in Additive Manufacturing Thermoplastic Components

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The following article extends and tests computational methodologies of design to consider Finite Element Analysis in the creation of optimized infill structures based on regular and semi-regular patterns that comply with the geometrical constraints of deposition. The Stress-Deformation relationship manifested in Finite Element Analysis is structured in order to influence the geometrical arrangement of the complex spatial infill. The research presents and discusses a program of performance informed infill design, and validates the generalizability of a method of internalizing and automating Finite Element Method (FEM) processing in Fused Deposition Modeling (FDM) workflows, and tests manufacturability of the methods through its ability to handle the FDM process constraints of FEM influenced intricate geometries.

Keywords: *Additive Manufacturing, Finite Element Analysis, Fused Deposition Modeling, 3D infill*

BACKGROUND

Additive manufacturing (AM) has seen an exponential growth of application in architecture and construction since the release of several technique patents. Among the most commonly used AM techniques in architecture is Fused Deposition Modeling (FDM), a process based in the numerical control deposition of a plastic material. FDM is an additive manufacturing process based on the principle of stacking layers of a material of plastic consistency through a numerically controlled deposition system. This process builds an object designed previously from a computer-aided design model.

Generally, the understanding of the fabrication process is overridden, since it is an automated process in which a closed mesh or poly-surface is imported in a software that makes a stereolithography format file (STL).

One of the principal affordances of Additive Manufacturing to architecture and construction is that it enables cost efficient production of highly complex forms and recent advances in Fabrication Techniques of Architectural Scale Additive Manufacturing (AM) and Spatial Fused Deposition Modeling (Mueller, Im et al. October 2014) with ad hoc computational methodologies of design of structural and functional components provides critical cost (de Soto, Agustí-Juan et al. 2018) and time productivity (Bock 2015) innovations in construction automation of highly complex forms, continuously increasing freedom of design and opportunities for global optimization by engineering local differentiations (Hack, Lauer et al.

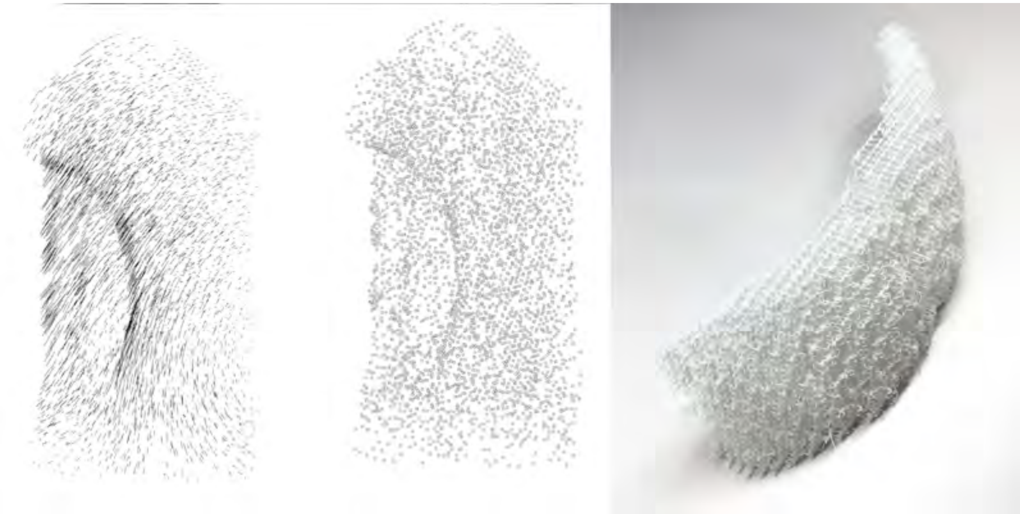

Figure 1
Custom 3D printing of cellular structures

2014).

The 3D printing process distinguishes two major parts, the outer perimeter or boundary of the object, and the interior of the object or infill. Recent efforts focus on topological optimization of the global shape. The parameters of both, the outer layer and the infill can be modified in the STL generator software. However, while we can choose between a limited set of options, infill design is not considered as part of the design process. Customizing the deposition process, as in spatial 3D printing, allows design criteria to be implemented at a material performance level (Ladron de Guevara et al. 2019), further enabling control over the geometry.

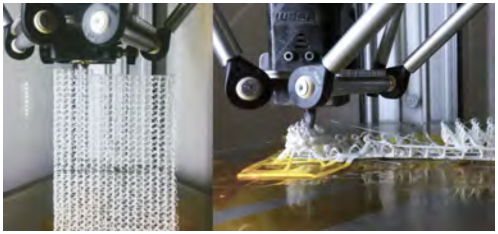

Figure 2
Cloud of threads in multi-resolution spatial 3D printing

Studies of architecture and large-scale production of structural components exhibit that a competitive time of fabrication and a correct simulation of anisotropic mechanical properties are among the main challenges for future development of the manufacturing process. This research studies the digital design itself, previous to the manufacturing process, to further optimize the material distribution and robotic toolpath production, potentially increasing the performance and time required for production of the processed components, as the principal area of opportunity for significant improvement.

The regular network of threads produced in standard FDM is characterized by having an anisotropic mechanical behavior (Ahn, Montero et al. 2002). Locally influencing the thread deposition during FDM based on FEM simulation results has demonstrated successful transformation of mechanical properties (Gospill, Shindler et al. 2017).

Commercially available Slicing software (Cura, Slic3r) include undifferentiated 3D infills, interesting for their better mechanical properties as compared to continuous vertical extrusion of patterns in 2D solutions. These geometrical designs present yet some challenges for successful FEM simulation, as some of the manufacturability aspects.

Newer developments in slicing software include variations in density and the possibility of manually introducing infill density differentiation by varying the percentage of solid and empty parts within volumetric thresholds defined by solid meshes interior to the global geometry. In this technique the resulting infill are processed and computed as independent volumes, useful for resolution or coloring purposes but fragile in their mechanical performance due to the discontinuity of fibers at volumetric threshold limits (Borunda et al. 2019).

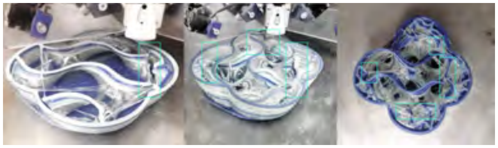

Figure 3
Fiber discontinuities in processed token with density variation by commercially available slicing software

Influencing the infill design using FEM Analysis is a current topic of study. This research builds upon methods for introducing computational workflows that incorporate Finite Element Analysis (FEA) (Chronis, Dubor et al. 2017, Gospill, Shindler et al. 2017) in the design of functional components to apply stress informed AM fabrication techniques (Tam, Mueller 2017) in the fabrication of spatial structures by locally differentiating the deposition of material, specifically tailored for a given application to increase the opportunities for optimization of the mechanical properties of the studied component. A reduced environmental impact can be another significant development in reducing material waste.

Figure 4
Unstructured discretized individual values at full Finite Element Analysis resolution divided into 3 isostatic cloud thresholds, low strain, mid strain and high strain

The purpose of this research is to explore where we are heading regarding construction automation by additive manufacturing of informed geometries, particularly exploring the potential improvements to layer by layer Fused Deposition Modeling applications in manufacturing of functionally graded components (Loh et al. 2018), to give insight into digital design workflows that consider impact of data in the geometrical composition and material constitution of form.

METHODS

The characterization of mechanical behavior in functionally graded components show several potentials in maximizing performance of building component manufactured with FDM techniques. The approach presented in this paper evaluates the potential use of strategies common in bone development (Gibson 1985) of density variation, and a characterization of mechanical performance along the principal stress lines resulting in a foam-like behavior (Gent, Thomas 1956) of the porous cellular solid. AM techniques such as FDM show exceptional capacities of producing very complex structures.

The process of fused deposition requires the serialization deposition process of a continuous robotic toolpath in discretely computed units (Retsin and Jimenez Garcia 2016). A method for automating the infill differentiation that maintains continuity of fibers and density variations based on Finite Element Analysis can potentially produce highly differentiated mechanical properties for functionally graded building components, with no need of changing material. Foam-like infills manufactured with FDM can be successfully adapted in isotropic to anisotropic mechanical behavior by varying the deposition toolpath. By control of differentiated density infill based on FEM stress results and deformation, vectors of displacement may provide stiffness and increase performance.

After important developments in layer by layer principle of manufacturing, such as advances in industrial grade deposition systems and advances in material engineering, the technique is currently being exploited in an increasing amount of architectural projects. Computational methods of utilizing Finite Element Method (FEM) analysis to optimize components by engineering the internal material distribution based on complex three dimensional patterns (3D infills) are presented.

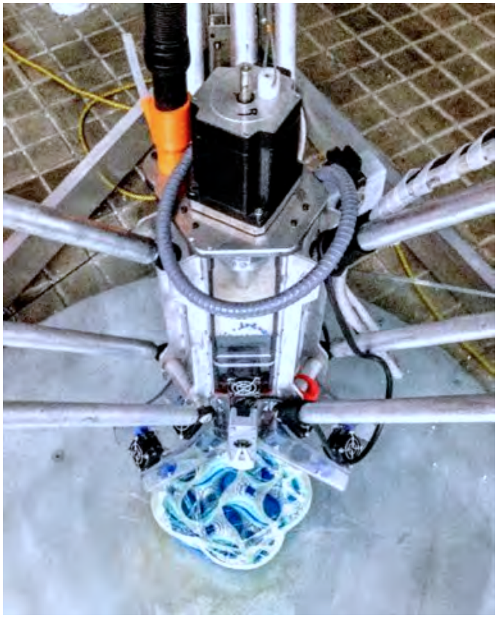

Figure 5
Polyhedral 3D infill with continuous fiber deposition

FEM TO GCODE WORKFLOW

Complex structures are susceptible of Robotic AM for their generalized geometric logic, adaptable to algorithmically design processes by means of discretization of a global geometry in a concatenation of local manufacturable geometries. Each of the computed units, are therefore, directly related to an index corresponding to FEM analyses.

From a holistic point of view, a global geometry is constructed and analyzed with a series of FEM analyses. The result of these analyses informs the construction of a new customized infill that must optimize and improve the rigidity of the piece without any morphological change at the skin of piece. Respectively, the contribution of this research lies in the creation and corroboration of a method for the design and optimization of the infill structure of fused deposition modeled components for the fabrication of digitally designed complex surfaces composed of discrete polymer components.

The characterization of fibrous structures that perform as cellular solids based uniquely on their geometrical difference provides further insight in the use of several types of infills for different density applications.

This research takes a non-structural dented triangular column as a case study and explores the potential of infill variations to accommodate a priori instability to a successful manufacturable column, based on an FEM-informed redesign of the infill pattern that builds on differentiated complexity and rigidity.

We depart from a vertically extruded filleted-angle triangular shape and apply some denting force until FEM analyses produce unsatisfactory results. Once the geometry is suitable to be reconfigured with an informed infill pattern, we build an algorithm that identifies localized stressed points and transforms the infill pattern at the stressed areas to elevate its rigidity level.

Custom feedback loop and data links are required to FEM process FDM pieces, a standard workflow is yet to be developed. The generalized process proposed for this research follows:

1. Geometries are modeled in gh-python for Grasshopper, plugin for Rhinoceros software.
2. Geometries are imported to SimScale Cloud based FEM for discretization and analysis.
3. ParaView unstructured data is exported as csv tables through python shell.
4. Tables of data are imported back to Rhinoceros using Python.
5. Custom python components in Grasshopper parse data and create geometrically continuous deposition infill designs as a list of coordinates.
6. The list of coordinates is computed as Gcode commands.

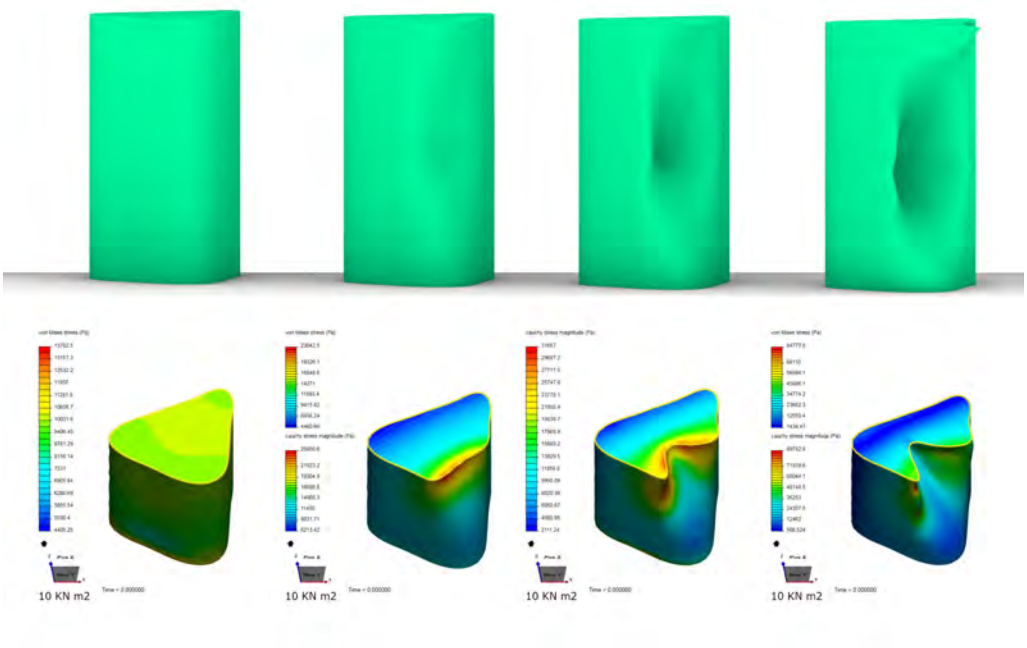

Figure 6
Sequence of applying denting force until FEM analyses yields unsatisfactory structural results.

The set of coordinates in a table is transferred to commands for 3D print. The Gcode Commands must review that each point is not self-intersecting and is be structured following a generalized method of deposition. Each point of the list can be categorized in the following:

- Base: for which ventilators are turned off, flow is increased and speed is reduced.
- Knot: a point or line to be fused with previous layer for which ventilators are turned off.
- Thread: a line in space with cooling system on. Speed is reduced.
- End point: stops extrusion and gently lifts nozzle for initiating a no-extrusion traveling movement.

The computational method is tested in dented designs, particularly susceptible of concentrating stress, therefore significantly benefiting from a highly differentiated material distribution and infill layout. FEM influenced FDM is particularly relevant for the production of singular instances of performative and parametric models in digital design due to their intrinsic complexity. A set of parametrically design dented structures (Figure 6) is modeled and fabricated for the purpose of testing variable matrices and infill mechanical performance.

This dented geometry is discretized in external cloud based simulation SimScale. The discretization process hinges on 3D mesh generating system common for Fluid Dynamics simulations. This 3D mesh provides a system for indexing stress values in

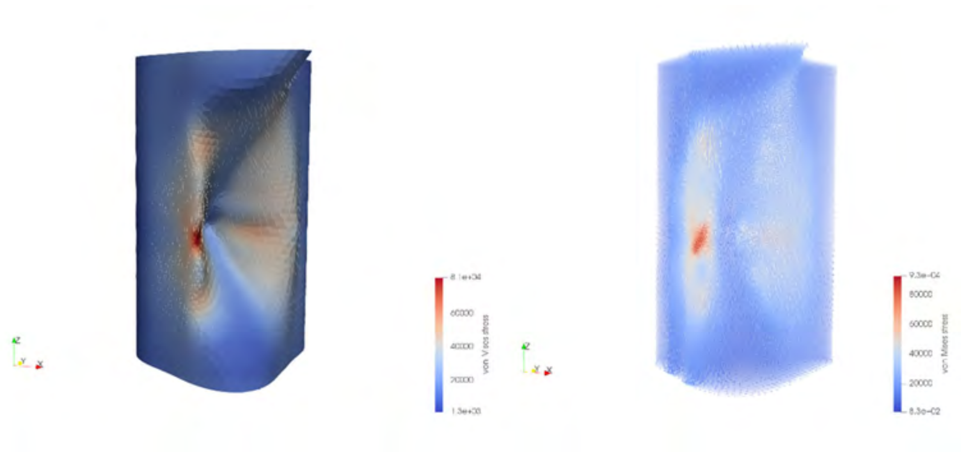

Figure 7
Indexed stress values in a 3D mesh structure

3D space (Figure 7) accessible through Visualization Toolkit (VTK).

The design process analyses the studied component, a filleted triangular column by overlying the 3D surface of the model with its FEM paraview output.

DESIGN METHODOLOGY

The design method comprises a feedback loop process in which FEA analyses inform a proposed three-dimensional infill pattern. Since it is structured based on a three-dimensional grid with different resolutions, a combination between a layer-by-layer approach and a spatial printing technique is required. The infill is no longer a fixed two-dimensional pattern repeated layer by layer. Rather, it assumes a principal role in the design process.

While the perimeter of the object is independent form this process, being naturally designed first, the design of the infill goes into a loop until the FEM analyses meet. An algorithm joins perimeter and infill at each loop iteration, ensuring the unification of both parts. The results obtained from finite element analysis (FEA) engineer anisotropic plastic components by discretely determining infill-like spatial polyhedral geometries. In order to produce bespoke infill patterns, a computational method of data processing based on a graph data structure is required in order to relate two different object classes that manipulate FEM data such as a singular data-point and a singular data-layer, with a class that creates infill patterns.

Initial indexing of cells takes place with the internal discretization process of a global shape. This provides an index to each one of the particles that composes an isostatic cloud. As each cell is composed of geometrical and performance information referenced to one point, it is possible to access this information in the software Paraview, from where a table of results is extracted in csv format. This extraction process is automated in Python, and the abstraction of geometrical and spatial values in a table enables the successful processing of samples in orders of magnitude superior to 100.000 samples with a commercially available processing equipment.

We take unstructured results from stress analysis data sources in isovolumes and isosurfaces in order to locally differentiate the composition of plastic tokens (density, mechanical properties and fidelity) based on different analyses such as associated stress values. This set of samples, compounded by units in the isostatic cloud list of points, stress values and deformation vectors is processed by an algorithm that organizes the data, converting the unstructured FEM data to a structured object classes. After applying the underlying structure, an ordering algorithm indexes the isostatic cloud by layers, and outputs it ordered by Z key, that is, first re-structuring by interpretation of values in order of height, as the deposition process requires, then, negotiating in relationship with the global set results and the neighboring results of the specific geometrical design and value of density of the sample.

Internal discrete structures can greatly enhance overall material performance, specifically strength and stiffness are evaluated and improved. We in-

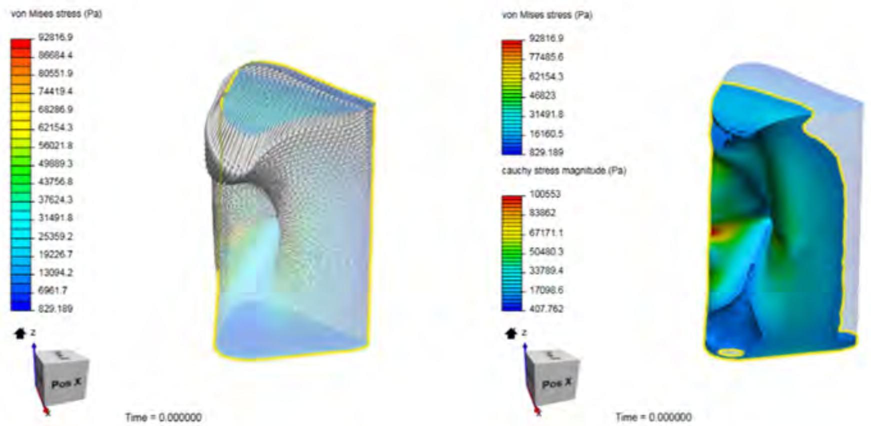

Figure 8
von Mises stress values on studied dented surface

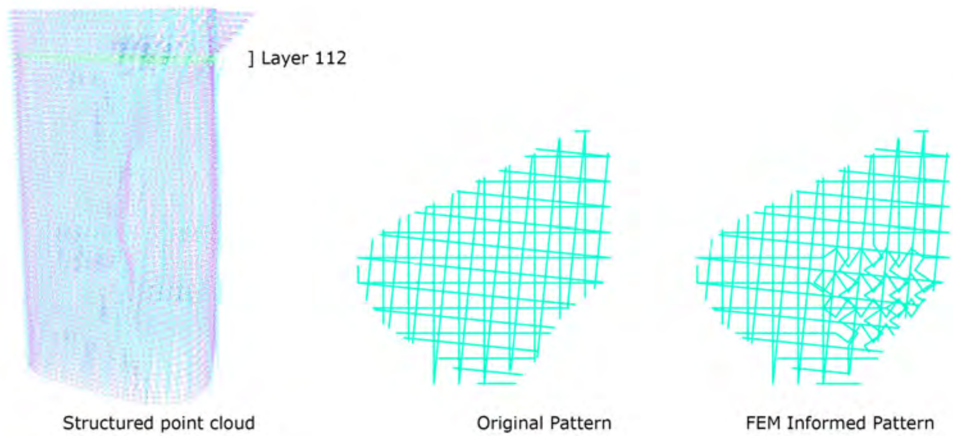

Figure 9
Original pattern vs FEM-informed pattern at localized stress area.

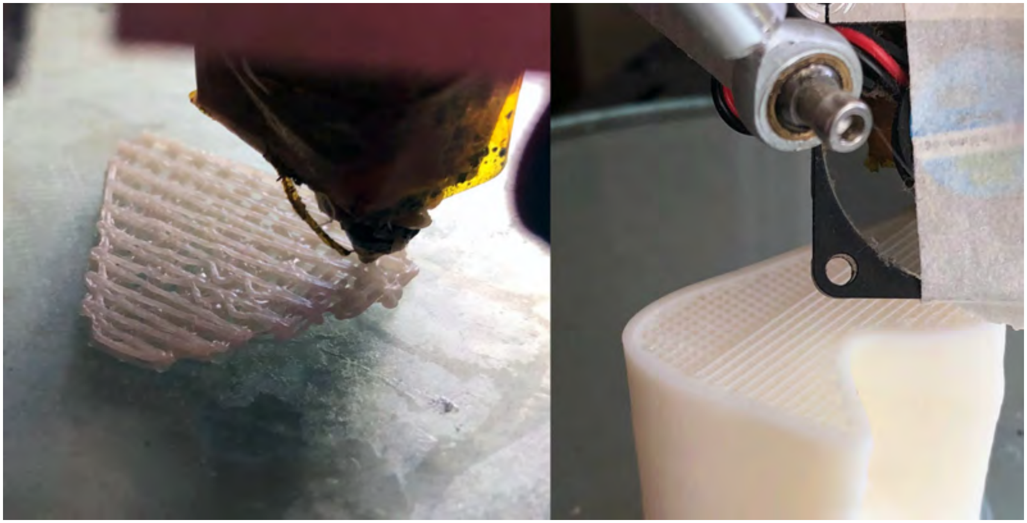

Figure 10
Informed infill layer vs default infill from Gcode exporter software

crease performance while potentially reducing material use and manufacturing time, two of the main constraints in adapting the rapidly growing use of additive manufacturing in larger scale applications.

The design method workflow is applied to robotically augmented additive manufacturing techniques and large scale industrial additive manufacturing techniques. The paper validates the method through testing FEA to FDM processed tokens and standard infill designs at different loading scenarios.

COMPUTATION OF INFORMED INFILL PATTERN

The algorithm creates and indexes a set of points that correspond to discrete areas of horizontal sections. This set of points creates an infill pattern by connecting each point with polylines, in a process similar to what any current default Gcode exporter software does to 3D print a component – namely, Cura, Slic3r, or OctoPrint –. The algorithm then, redesigns the mentioned patterned infill, informed directly by the FEA process. This allows us to create customizable intelligent infill geometries that make localized densities respond to structural analyses.

Computationally, points are organized through an underlying graph data structure in which each point is represented by a vertex, and it is connected with its neighbors by edges. The vertices of the graph are dictionaries of data that contain 3D points in space, and information about their location, the FEM result at this precise location and the quantity and quality of its neighbors. We map the result from the FEM analysis to level of priorities. The more critical the smashed surface is, the higher level it has, and the more neighbors it creates in order to get it optimized until making it pass the FEM analysis again. It is important to say that each index is aware about its neighbors, and its neighbors about their closer ones. What it drives the configuration of the total point cloud is the information residing at each vertex. Based on each neighbor's levels, a particular point may re-adjust its position to satisfy the holistic configuration.

RESULTS AND DISCUSSION

Current computational power opens up new design methodologies, shifting the conventional visual-feedback design process in architecture to a more scientific approaches. This paper presents an optimization workflow for structurally unstable surfaces to find a successful solution by informing the infill pattern through FEM analyses. Its contribution lies in presenting an alternative of making successfully stable complex surfaces without the need of modifying the global shape. A general understanding of programming and FEA tools is required, also, combined with the ability of producing an anew gCode. While available gCode generator software is only a tool for quick manufacturing that exists at the end of the design-fabrication process, we understand there is an opportunity of design intelligently by inserting the gCode stage earlier in the overall process.

Methods for translating unstructured data obtained from other Computational Analysis by Finite Elements into geometrical 3D infill data in continuous deposition toolpaths can be implemented, not only to allow for mechanical behavior improvements but to introduce novel information workflows into the design and manufacturing processes.

Even though a new customized infill is created that responds directly to the specific dented surface, this is only one step towards a full customizable infill design. A singular pattern has been developed, demonstrating the close connection between FEA models and FDM. Further research will make a comparison between different design infill approaches, will test their mechanical properties and will produce an outcome to determine the most optimized infill that meets the specificity of the studied piece.

This research explores a previously unexplored territory in architectural application, and offers an alternative to make structural, and therefore, manufacturable to a priori non-suitable geometries.

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Challenges - CULTURAL HERITAGE

DIGITAL MODERN

'Towards a new materiality' of Modern Architecture in Fortaleza-Ceará (Brazil).

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The topic `Digital Modern' is a metaphor for expressing the importance of the valorization of Modernism in the current stage of capitalism and in the context of the 4th Industrial Revolution, marked also by the inclusion of the virtual/digital in architecture design, ``towards a new materiality''. Linking, past, present and future, this paper aims to discuss the importance of documentation of the most emblematic modern works of Fortaleza, capital of Ceará (Brazil), using digital technologies, such as the BIM platform and 3D printing, with the goal of contributing to the valorization of memory and conservation of this important architectural heritage.

Keywords: *digital modeling, modern architecture, BIM, digital documentation, Fortaleza-CE (Brazil)*

INTRODUCTION

The word 'modern' has Latin origin in *modernus*, which means present, up to date, which belongs to recent times. In architecture, the term is a paradox, as long as the modern is already past. Since the Renaissance, the term is used to designate an opposition to the old and, at the beginning of the XX century, it consolidates as an adjective that signals a rupture with the classic tradition, identifying with the modernization triggered by the Industrial Revolution and with the Modernism, that is, the cultural and artistic expression of modernity. Thus, the Modern was used to qualify an artistic and architectural production committed and engaged with the alignment to the material progress of humanity, impacting the urban and architectural production in a hegemonic way in different places of the world, projecting itself for the future.

The topic 'Digital Modern' is a metaphor for expressing the importance of the valorization of Modernism in the current stage of capitalism and in the context of the 4th Industrial Revolution, marked also by the inclusion of the virtual/digital in architecture design, 'towards a new materiality' (Picon, 2004).

The digital age enables every object and every material, at each stage of its elaboration, to be rigorously defined. True novelty might very well lie ultimately in the generalization of design, as a practice regarding not only buildings and their various technological systems, but also materials and beyond them nature as an engineered reality (Picon, 2004, p. 120).

At this time of transformations in the materiality in the representation and architecture design, it is fundamental: to recover the importance of the built collection of modern architecture and consider it as heritage; to discuss the state of continuity and validity of modernist principles in contemporary times for the design and intervention in existing buildings and; to incorporate digital technologies as toos of valorization, documentation and conservation of the modern architecture. In all the previous statements mentioned, it is essential to articulate past, present and future, referring to the transformations in the materiality of architecture.

Many studies have been devoted to the use of digital technologies to produce knowledge about heritage. The virtual (re)construction of modern architecture in Fortaleza, Ceará, in the Northeast Region of Brazil, through the digital modeling and prototyping of the most emblematic buildings, presents as a possibility to extend the existence of this built heritage, either by rescuing the memory of demolished buildings, resuscitating them, or by valuing the remaining collection.

The production of the digital documentation of these works constitutes an important contribution to the historiography of the architecture in Brazil, being an instrument of preservation of the memory of this architectural heritage. Although it belongs to a recent past, it presents many examples already demolished or in advanced stage of degradation.

Thus, this paper aims to discuss the importance of documentation of the most emblematic modern works of Fortaleza, capital of Ceará (Brazil), using digital technologies, such as the BIM platform and 3D printing, with the goal of contributing to the valorization of memory and conservation of this important architectural heritage.

THEORETICAL ASSUMPTIONS: THE DIGITAL REDRAWING

The materiality of architectural drawings often does not withstand the passage of time, making it difficult to understand the genesis of the building and the memory of the architectural design that since the Renaissance has elevated the status of the architect and irreversibly altered professional practice. There is no doubt that the techniques of design and registration of modern architecture were also impacted by the new possibilities of representation provoked by the technological advances of the Industrial Revolution. Thus, the most recent architectural patrimony, especially the modern one, had the privilege of having the drawings of its most emblematic samples published in specialized magazines and monographs on the most outstanding architects.

Either with or without the permanence of original designs of historic buildings (modern or not), the redrawing is an important tool of historical research, since it constitutes *"a metalinguistic practice, that is, an intentional and directed design simulacrum: a project of the own project "* (Ramos, 2016, p.5-6), as long as it allows to deepen the knowledge about the past, the present and the future of the building, its conception, materialization, as well as existing and planned interventions.

The advent of new digital technologies and their impacts in the area of Architecture, Engineering and Construction have contributed widely to the dissemination of knowledge and played a relevant role as an instrument, not only for design, development of the project, generation and management of information, but also for the materialization and innovations of great value for the documentation and even intervention in the architectural and urban heritage.

Thus, an *"emergent materiality"* (Picon, 2004) has also influenced the use of redrawing in historical research, although, researchers in the urban and architecture history are not always involved in the construction of the 3D model. *"The recognition of the modeling process importance to the historical analysis and research depends often on the interaction between those two groups"* (Kos, 2002, p. 507). It is important to note that a new materiality is under way in the process of documentation and conservation of historical heritage.

Since they are not static, but dynamic, digital representations introduce in the architecture research (his-

torical, critical, analytical, etc.) possibilities of approach to the architectural object that neither the traditional analogical means , nor the original drawings contemplate. The mobility of the image and the possibility of wandering through the work, although virtually, open an unknown interpretive field. Even modeling with parametric software can bring new types of data, such as quantitative ones, that have never been used in historical research (Ramos, 2016, p. 5).

Among the various technologies, Virtual Reality, Mixed and / or Augmented Reality, Web Technologies, GIS, CAD, BIM, Rapid Prototyping, Digital Fabrication can be highlighted.

The BIM (Building Information Modeling) consists of privileging a contextual construction, supported by an intelligent simulation of the space-form relationship, replacing the traditional abstract representation of fragmented communication conventions. (Andrade; Ruschel, 2011) The construction of the object in BIM has as its premise a central information model, in which abstraction is replaced by simulation, that is, it evolves in an analogous way to a virtual design process. In case of using it for documentation, it may be employed for restitution of the object built or already demolished.

It is still possible to comprehend BIM from what it is not. Thus, it is not considered BIM platform software, whose archives: (i) it only contains digital three-dimensional models without attributes, rendering project analysis and data extraction and integration impracticable; (ii) that it does not use parametric intelligence, hindering the generation of views and making them incoherent and imprecise; (ii) it contains multiple references of uncombined 2D CAD files in a feasible 3D model; (iv) that it does not allow automatic changes in views when there are changes in dimensions (Estman et al, 2014).

Descending from BIM, Historic Building Information Modeling (HBIM) has a specific role focused on documentation, analysis and conservation. It is a reverse engineering process that, through the mapping of the architectural elements, uses as a resource a laser scanner or photogrammetry. For Murphy; McGovern; Pavia (2013, p. 89):

Historic Building Information Modelling (HBIM) is a novel solution whereby interactive parametric objects representing architectural elements are constructed from historic data, these elements (including detail behind the scan surface) are accurately mapped onto a point cloud or image based survey. (...) Full engineering drawings orthographic, sectional and 3D models can then be automatically produced from the Historic Building Information Model.

Overall, HBIM has been used more for documentation of older buildings than for modern ones, perhaps because it functions as a very suitable feature for scanning ornamental elements and building details.

For Kos (2002), digital modeling is more than simply a representation, it constitutes a digital/virtual research database, which brings together primary sources, images, drawings, documents, vectored or non-vectored collections, functioning as the matrix of historical research on the built patrimony.

PRACTICAL ASSUMPTIONS: (RE) CONSTRUCTION OF MODERN ARCHITECTURE IN FORTALEZA

Modern architecture in Brazil developed in a heterogeneous way in time and space, due to the different forms of articulation between the emitting and receiving centers. In Ceará, the penetration of the principles of modern Brazilian architecture are related to the displacements of *"migrant, nomadic and pilgrim architects"* (Segawa, 2002), responsible for the conception of the first modernist projects and involved with teaching, in the case of Fortaleza, in the context of creation of the School of Architecture of the Federal University of Ceará in 1964. In addition, it is important to highlight the production of works by some Brazilian architects in Fortaleza. The prominence of these modern architects constitutes a relevant contribution, especially the legacy of the constructed works.

This paper is a product of an empirical research that involves the modeling of 52 buildings that are included in the Guide of Modern Architecture of Fortaleza (1960-1982).

The digital (re) construction of these buildings implied the need to systematize the iconographic sources and confront them with the empirical object (in the case of the remaining buildings), since the work *"has in itself the most meaningful data for its knowledge"* (Waisman, 2013, p. 11), allowing to infer about the mismatches between the project and the work and the transformations and interventions suffered over time.

In order to organize and standardize the information collected, a database has been produced to document and to systematize the information that was compiled in building characterization sheets. However, the database is not restricted to the fiches, since primary, secondary sources were collected and the virtual modeling designed in Archicad constitutes the most important process and product of the digital documentation.

For the digital modeling, the Archicad 20 software, based on BIM technology, has been used.
The choice of this software is justified by the capacitance to store information with reduced file sizes, facilitating its use; rapid learning curve; interoperability; easy navigation; free student availability and export effectiveness in a variety of formats.
Following, the 3D impressions of buildings are being produced.

RESULTS

One of the main results of the research is the construction of the digital database.
Out of the total of 52 works that comprise the scope of the research, 45 models were completed (Figure 1) and 7 are in the development stage.

As a complementary product of the digital modeling, sheets were adopted, which allow to establish parallels and comparative studies between the works, as well as parameters of the building analysis. Among the items that make up the characterization sheet, it is possible to highlight: the name of the building, the use, the architect, the constructor, the date, the land areas, location, situation map, images and references.

Figure 1
List of 3D Model - Modern Architecture in Fortaleza

The sheets are being produced in two formats: the first as a banner, with synthetic information and greater graphic appeal, which will be used in physical and virtual exhibition (Figure 2); the second, as an inventory, gathering in-depth information about the works, drawings and 2D and 3D images extracted from the digital modeling (Figure 3).

Figure 2
Example 3D Model Banner

In addition to the dissemination and availability of the research product (modeling and sheets) on the website of the Guide of Modern Architecture in Fortaleza, the research contemplates the insertion of the model and digital documentation in the BIMx software, which consists of a "hypermodel" (format.bimx). The BIMx Model may contain complete documentation of your ARCHICAD project: the 3D model, as well as views, layouts and camera paths (Figure 4). It expands the horizons of documentation of modern buildings, making it easy for architects, engineers, ordinary users and customers to access through diverse accessible platforms (computer, mobile, tablets). For the general public, it extends the possibility of apprehension, understanding and new interpretations through insertion within the 3D model, besides facilitating access to information, contributing to the knowledge, valorization and consequent preservation of this built heritage. In order to control open access, it is possible to leave it private and password-only access for registered users, who must commit to the educational and academic use of the data.

The final product of the research is to perform a physical and virtual exhibition of the modeled buildings, showing the entire digital modeling process, from primary sources to 3D printing (Figure 5).

The 3D printing process is being developed in partnership between LoCAU (Laboratory of Critics in Architecture, Urbanism and Urbanization) and LED (Laboratory of Teaching, Research and Extension in Digital Design), both belong to the Department of Architecture and Urbanism and Design of the Federal University of Ceará. The research also counts on the support of scientific initiation scholarship students from both laboratories.

In the site of the Guide of Modern Architecture of Fortaleza (1960-1982), which will host the modeling, there will be a search system related to the routes, different typologies and the architects authors of the projects, as well as how to allow updates and additions of new works.

Still as a research product, it is worth mentioning that the models are used in the last discipline of Architectural Design in the Course of Architecture and Urbanism of UFC, whose theme is intervention in existing buildings. At the end of the research, as a counterpart to sources provided by companies and public agencies, digital modeling will be made available to stakeholders and can serve as an important support for the management of interventions in buildings.

FINAL REMARKS

The drawing, as a principal means of representation in the field of architecture, plays a fundamental role

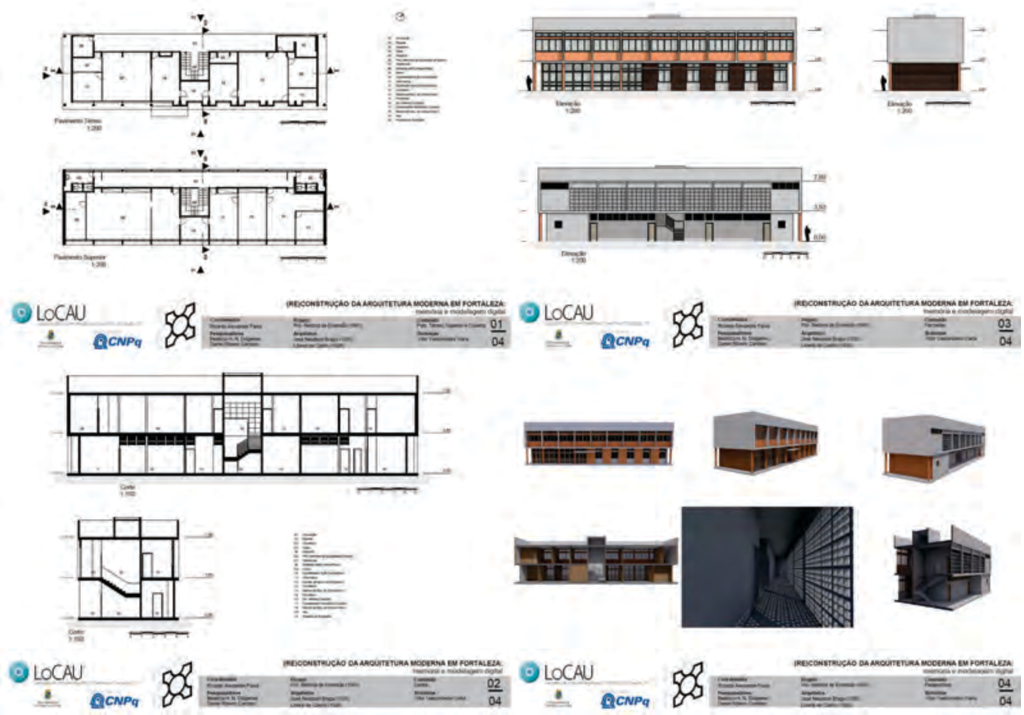

Figure 3
Examples of detailed characterization sheets

to make the project *"intelligible, viable and transferable and, as such, it constitutes a symptom of technological and cultural development in a given historical-social context"* (Paiva, 2015, p.3). At the service of art and technique, often synthesized and present in the architecture, the drawing constitutes historical document and legacy of the material production of humanity, in addition to the buildings the drawing represents.

The means of representation maintains a dialectical relationship with technology, insofar as they are means and ends, that is, they intensify the technological development at the same time as they compose it. The adoption of new digital means of creation, representation, documentation and information in architecture has led to an ongoing process of replacing more abstract representations with simulations of the object to be constructed, with the increasing approximation of representation to real objects.

The new digital technologies must be incorporated as an allied in the process of documentation and conservation of the architecture, being BIM an important platform for parameterization and information of the built heritage, allowing possible referrals regarding the intervention in the existing building and consequently its preservation.

In this field, digital redrawing has a great potential to rescue the memory of projects and buildings, which can be promising in the modeling of buildings that have been decharacterized or demolished, since *"the object that witnesses our past disappears, its*

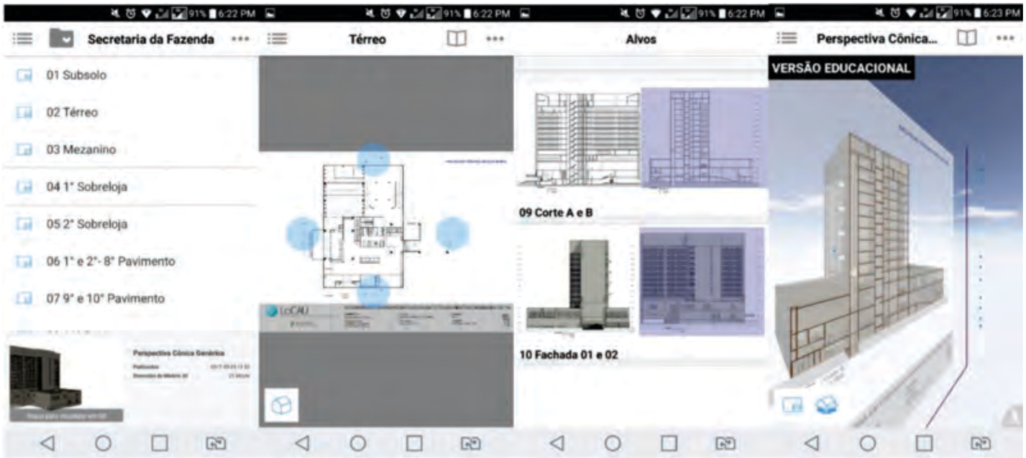

Figure 4
Interfaces in smartphone of the BIMx program with the 3D model of the headquarters building of the Ministry of Finance

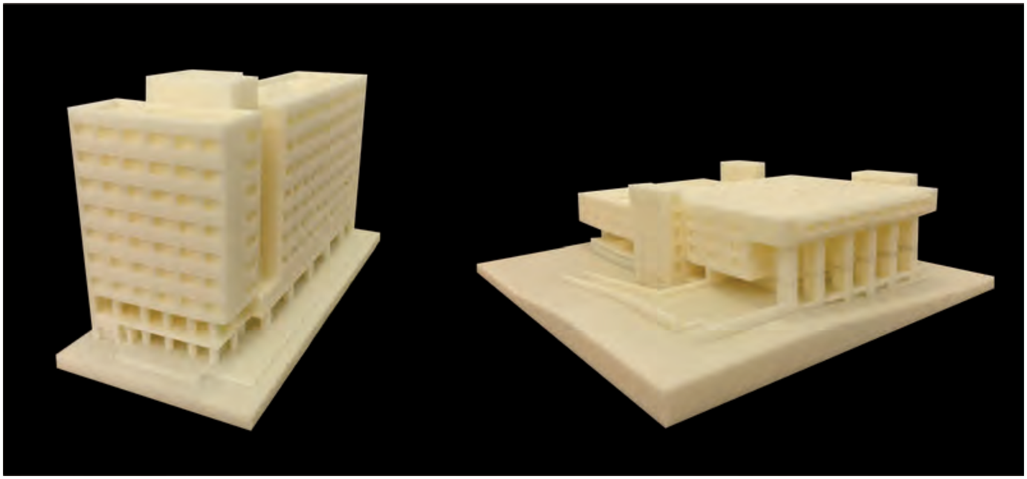

Figure 5
3D Printing Examples - Palácio Coronado Buildind and Education Secretary of Ceará, both designed by José Neudson Braga. Produced at master degree research by Cristiane de Araújo Alves Siqueira denomined 'Neudson Braga e o modernismo arquitetônico em Fortaleza'.

image can replace, though in part, the immanent need of human nature to keep in touch with what has gone. Hence one of the several uses of cadastral representations as a way of preserving memory" (Oliveira, 2008, p.13). Thus, expanding the limits of documentation by adding new forms and platforms of modeling and documentation towards a new materiality will contribute effectively to historical research.

The research has interfaces with studies dedicated to the subject and has found a privileged forum for discussion and dissemination of knowledge in seminars about the Modern Movement, such as the various editions of DOCOMOMO Conferences (international, national and regional), as well as on the use of digital technologies in historical research as SIGraDI.

The production of these digital models enables a new way of documenting modern works in Fortaleza, contributing to the historiography and expanding the possibilities of interpretation and apprehension of its essential characteristics, such as the structural system, constructive materiality, spatial solutions, formal expression, among other aspects.

Finally, this article synthesizes a research that is a development of education, research and extension activities at the undergraduate and postgraduate levels, contributing to the formation of architects committed to the issue of built heritage, which is widely threatened by contemporary urban dynamics. Thus, the idea of 'Digital Modern' is a way of understanding the transformations that contemporary technologies impose on the way of perceiving, representing and intervening in these buildings 'towards a new materiality', making its existence last.

ACKNOWLEDGEMENTS

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Gamification of Heritage through Augmented Reality

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This paper focuses on a game on architectural heritage, possibilities for using gamification for conveying information through the reanimation of an ancient city. It proposes an immersive AR game involving the portrayal of cultural heritage through mobile devices. The game includes an AR application for Android devices which enabled rendering of 3D content in combination with camera input. This application is an independent game, tracking targets through GPS on a larger scale and using object recognition on a smaller scale. Our research aims to propose implementing game mechanics on an AR system at an archaeological site in order to increase visitors' interest, and promote the dissemination of cultural heritage.

Keywords: *digital heritage, model-based tracking, augmented reality, gamification, public archaeology*

INTRODUCTION

Ancient cities of archaeological excavations function as sites of both scientific research and public exhibition. Usually, long-term archaeological research means postponing the preparation of the site for visitors. Public engagement is often further delayed by the need for rigorous research involving data collection, documentation, analysis and interpretation of the artifacts. The practice of archaeology with the participation of the public is known as 'public archaeology', defined by Moshenska (2017: 7) as "all the work of state-controlled or -funded bodies on national, regional and local scales to manage, preserve, study and communicate archaeological heritage". Public archaeology has come to refer to heritage management in a general way, but this term can be misleading if it focuses on the interests of the archeologists in preserving cultural heritage, at the expense of the interest of the public (King, 2012). In some archaeological excavations, the interests of the locals have been neglected. One of the most pressing concerns facing archaeologists and cultural resource managers is how to protect cultural resources for meaningful research and future investigation while ensuring access to the citizens, who in many cases, are the true owners of the resource.

The public interest and engagement with the heritage may be achieved through digital public archaeology. This 'digital' form of public archaeology involves engaging the user with archaeology by means of web and mobile technologies, social media applications, and the communication process by which this commitment is mediated online. The internet allows direct experience archeological works in various formats through all stages of the process, from fieldwork through post-excavation (Richardson, 2013). According to Richardson, simply curating a website containing pages of hyperlinked text has lost its effectiveness in attracting serious public interest, and organizations need to use social networking activity, and to stimulate public engagement with the past through online presentation. In this regard, websites, social network platforms, video, podcasting, digital archives & repositories, and richer mobile content are all becoming more common (Watrall, 2011). Another enriched mediated content platform, Augmented Reality (AR), is also used for the visualization of heritage through informative and educational applications for visitors (Haugstvedt, & Krogstie, 2012). According to Dieck and Jung (2018), AR will become more valuable in near future because it reduces the need for information boards and other interpretive panels (including photographs, drawings, reconstructions, 3D views, models, maps, audio materials, etc.) for the presentation of outdoor historic and listed sites. The interaction between cultural heritage site visitors and AR systems will result in improved experience (Han et al. 2013). Among the aforementioned tools for public engagement with heritage, games, especially digital games, are now attracting more academic attention.

Games have played an important role in all known human cultures. Digital games, in all their various techniques and genres, are simply a new format of this ancient method of social interaction. Gamification refers to the adaptation of game technology and game design methods outside of the game industry. The dynamics of gaming are built on human desires, which may be rewards, status, achievement, self-expression, or competition. Gamification focusing on heritage sites and applications is gaining increasing value, because it engages visitors and allows for new means of interacting with cultural heritage information. Combined with the well-known formats of scavenging and treasure hunts, the practice of location-aware storytelling could enhance experiences related to cultural heritage awareness, and increase visitor involvement and engagement.

This paper focuses on gamification of heritage through the architectural reconstructions, i.e., the possibilities for using gamification for teaching heritage through representing various hypotheses regarding the reality of an ancient city (Varinlioglu and Kasali, 2018). The initial proposal is for a game entitled TeosGO, a treasure hunt game of immersive revisit of the cultural heritage through mobile devices. Based on current technologies, which enable rendering of 3D content through the camera input, we developed a mobile AR application for mobile Android devices (Varinlioglu and Halici, 2019). A single image-based tracking approach is not capable of recognising a 3D object from different viewpoints. With this approach, it is impossible to recognize a 3D model when the viewing perspective is changed, i.e., the image captured by the camera no longer matches the reference image. To overcome this deficiency, this study offers real-time, in situ 3D depiction and visualization of architectural artifacts of an ancient city implementing model-based tracking methods. Our research proposes implementing game mechanics on AR system at an archeological site in order to increase the interest of visitors, and thus improve the dissemination of cultural heritage.

REVIEW ON GAMIFICATION OF HERITAGE THROUGH AR GAMES

The term gamification refers to the approach of game thinking and game mechanics to increase motivation in non-game areas, and to encourage problem-solving. In other words, gamification can be expressed as the use of game design elements outside the normal context of games (Deterding et al., 2011). According to Gartner's Hype Cycle (2011), there has been a significant and growing acceptance gamifying process in many fields. Applying gamification to any activity encourages increased involvement and engagement (Brigham, 2015). Seaborn and Fells (2014) argued that gamification may be more accurately described as a subset of a larger effort to improve the user experience of interactive systems through gameful design, to increase user motivation, engagement and enjoyment in non-gaming, computer-mediated environments. Game techniques are added to existing educational processes in order to make these processes more interesting and attractive (Kapp, 2012). In this sense, a game-based learning environment in the archaeological domain will become more important for awareness-raising among visitors, and especially for digital natives. In addition, studies of serious games with educational objectives in the cultural heritage domain have focused on analysing the complex relations between genres, contexts of use, technological solutions and learning effectiveness (Mortara et al., 2014). In a cultural heritage context, implementing games, game-like activities, or game elements (badges, tokens, or similar mechanisms) enhances learning and engagement (Bujari et al., 2017).

Studies on digital heritage offer an interdisciplinary approach to historical sites, buildings, and artifacts, incorporating archaeology, restoration, and architecture. Recent developments in emerging technologies have led to the development of 3D archaeology, in which digital tools provide new perspectives on the collection, analysis, and visualization of data from archaeological excavations. Among these technologies, AR has great potential for investigating archaeological objects. Not only does AR provide a non-destructive way for archaeologists, art historians, and other scholars to analyze objects through high-resolution images, with no risk of damage to the originals, it also allows visitors to envision the 3D reconstructions of the ancient sites (Bekele et al. 2018).

The potential of gamified AR technologies has been studied at both indoor heritage institutions and outdoor heritage sites (Benckendorff et al., 2018). Hammady et al.'s (2016) study is a good example of a combination of indoor AR and gamification techniques in the Egyptian museum in Cairo. New technologies provide an uninterrupted illusion of a mediated experience (Riva, 2008). According to Weber (2014), location-based AR games seem to produce impressions of greater naturalness, as the boundary between the virtual and the real world disappears from the user's phenomenal awareness. In recent studies on outdoor cultural heritage, mixed techniques of AR applications have been preferred over solely marker-based AR applications. Archeoguide is a ground-breaking example of location-based AR implementation for the ancient city of Olympia and its ruins (Vlahakis et al., 2001). This implementation is based on the location and orientation of the user in the cultural area, with real-time rendering. Another implementation is KnossosAR, an outdoor mobile augmented reality (MAR) guide for Knossos in Crete, which integrates AR projections of interpretive information with a non-linear storytelling (Galatis et al., 2016).

Technology has advanced further than the methods mentioned above, and the latest mobile devices can track predefined 3D physical objects seamlessly. Model-based tracking systems, with their highly-advanced capabilities (Selvam et al., 2016), have great potential for site use. The emerging technology of the model-based tracking method makes possible real-time tracking of any physical object. The system requires pre-defined 3D models of the object to refer to as initial coordinate - reference point in the physical environment, and to superimpose virtual annotations.

This study aims to develop a mobile game based on model-based AR tracking methods, and to present 3D virtual archeological objects). Currently, augmented reality in archaeological excavations is mainly achieved by GPS tracking or image-based marking; in contrast, this project explores the use of model-based AR tracking technology to superimpose information on the artifacts themselves. Using model-based tracking technology within augmented reality environments, we aim to develop a mobile application suitable for expert archaeologists and non-expert end-users alike. Information pertaining to artifacts in the field, is conveyed by means of mobile devices, and thus provides an innovative additional layer of overall archaeological site experience.

METHODOLOGY OF AR GAME DESIGN AND DEVELOPMENT

This paper describes the integration of game design and development into the learning principles in order to increase the effectiveness of communicating knowledge about 3D reconstructions of the ancient site. The methodology includes a game design and development to enable visitors to experience the archaeological site. This is achieved by using GPS and model-based tracking methods for detection and overlaying created 3D reconstructions through an AR environment. Through a model-based mobile augmented reality, actual architectural artifacts are transformed into informed objects without disturbing the archaeological site. The evaluation phase of the game gives insights into possible further developments of an independent AR game.

Game Design

Game design is a broad field of computer programming, creative writing and graphic design. It is the art of applying design and aesthetics to make a game, whether for amusement, or for academic, exercise-related, or experimental functions. Game design should start with the gameplay, the combination and interaction of various elements of a game, although this stage is often neglected. Gameplay is achieved through game mechanics, the engineering concept of the gameplay, which refers to programmers' methods for determining interactivity within the game. Game mechanics are rules and procedures which govern how the game responds to the player's move.

The core concept of a game defines the narrative to be conveyed, and has three components: a theme, what the game is about; a premise, who you are in the game; and settings, how you play the game. This is often structured around a core recurrent/repetitive act. Rather than giving the feeling of being boringly repetitive, it provides a sense of progress through constantly raising the level of tension. Due to the unexpected and unpredictable nature of the action, we enjoy the continued repetition of the same act. The repetition of these actions ceases when a certain termination condition is reached, in other words, iterations are aimed at reaching a certain target, which ends the need for further repetition. The main rationale for repetitive movements is their eventual convergence, which is ensured by certain game rules and regulations.

Our game is a treasure hunt game, which involves collecting virtual points by finding AR objects and answering trivia questions (Figure 1). When augmented artifacts are found on site, the player wins virtual coins. Some players may miss some of the artifacts, and consequently may wander around the archaeological site, but through GPS tracking, players will be guided to other AR artifacts at various other locations on the site. The goal of this game is to motivate site visitors to explore while learning, and disseminate this learning to public during the site visit. We created the initial game mechanics by integrating various game elements, such as coins as collection dynamics and short quizzes to unlock the next destination point. Extending the role of AR in archeological site exploration, this study proposes new technology that facilitates new experiences, not only through didactic information transition by represen-

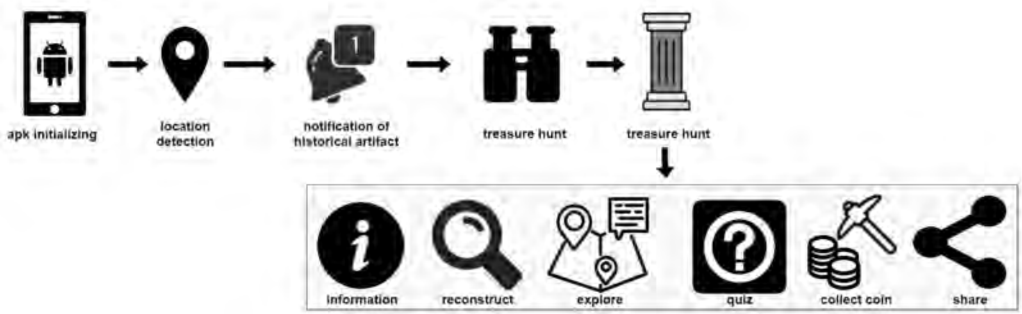

Figure 1
Flowchart of the game prototype

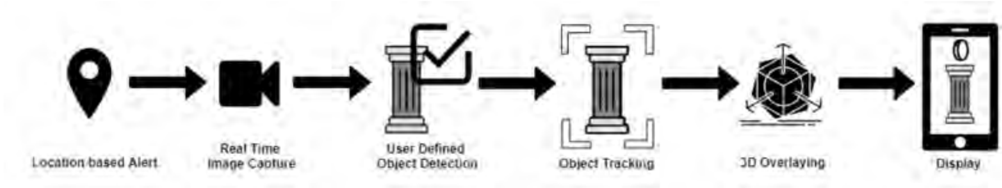

Figure 2
System architecture of the game prototype

tation, but also through immersive and pleasurable interaction.

The system architecture of this application consists of six steps: location-based alert initializes the second step, image capturing and activation of the tagged scene, followed by object detection, tracking, overlaying virtual data, and, finally, display (Figure 2).

Evaluation

The game design includes core concepts, game mechanics, aesthetics, character, levels, and main element narratives. The development of games brings together these elements to enable the realization of goals. Game developers start from the conceptual phase and make it into reality. In other words, programmers translate ideas into codes that computers can understand. A prototype game is a draft version of a testing game. The creation of a prototype typically marks the shift from the design stage to the development and testing stage.

Game testing is the discovery and documentation process during game development. Testing includes understanding players' real-time experiences through collecting feedback on their use of the application. The research focuses initial elements of the process, i.e., feedback on the gameplay, the usability of its components and screen elements, the clarity of its goals and rules, ease of learning, and enjoyment to the game developer. To understand the impact of the developed game on users, we conducted game testing with site visitors. A pilot test study was followed by a post-study questionnaire. The test group included expert users with previous experience at the Teos archaeological site and background knowledge of other sites.

Experts were chosen as a study group to create a more reliable comparison with existing applications, both on proposal applications, and for further development. The initial findings of the test showed that the test group successfully completed the artifact finding task in the site -treasure hunt- (Figure 3), and also the trivia quiz. However, it was found that the interface design, the game design components, and game mechanics need further development in future design stages.

Figure 3
Detecting the artifacts, collecting coins and experiencing AR objects

CONCLUSION

Digital public archaeology increases the public interest and engagement with heritage. This digital form of public archeology involves engaging the user with archeology through mobile technologies, social media applications, and digital games. This study presents the design, implementation and initial prototype testing of a low-budget augmented reality game for an archaeological site. Model-based object tracking technology is used to create a semi-automated guided tour for an outdoor archaeological excavation site. To maintain the integrity of the site, a markerless object tracking system is used for this AR mobile game. In other words, the artifacts themselves became smart heritage objects, providing an improved immersive experience in the archaeological site. This paper illustrates the use of AR in a combination with gamification method at the Teos site, showing the effective application of the concept of gamified ambient information in the field of archaeology.

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Parametric Beijing Siheyuan

An algorithmic approach for the generation of Siheyuan housing variants based on its traditional design principles

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Beijing Siheyuan is a type of Chinese vernacular housing with significant cultural value. During recent decades of economic growth, many Siheyuan houses have been destroyed; preserving the few remaining ones have become a necessity. Based on a historical analysis of their design principles, this paper develops a parametric model capable of representing its known variants. Our findings include a useful design tool able to efficiently represent existing or lost housing types and thus contribute to our understanding of the typology and their preservation.

Keywords: *Beijing Siheyuan, parametric design, algorithmic design, digital heritage*

INTRODUCTION

The Beijing Siheyuan (Quadrangle courtyard house, see Figure 1) is a historic housing type, once very common in the Beijing area. As an example of Chinese traditional architecture, it is an important part of the world's architectural heritage. After the Song dynasty, Beijing had a grid plan divided by hutong alleys, most of which were given over to quadrangle courtyard houses. The peak of Siheyuan development occurred in the Ming and Qing dynasties when it became the basic unit of old Beijing. Siheyuan is recognized as a typical representative of Chinese vernacular architecture. It embodies cultural values of traditional China, as for instance in the stipulation for different sizes of Siheyuan's houses made by governments which shows feudal hierarchy in ancient Chinese society. The constraint that all courtyards in Siheyuan are enclosed by walls or rooms illustrates the characteristic of introversion of traditional Chinese culture. In the morphological view, Siheyuan is a product with the obvious cultural identity of ancient China.

Figure 1
Photograph of Beijing Siheyuan houses and Hutong alley in 1989

Despite their cultural significance, the few Siheyuan houses that remain are facing oblivion, not only are the buildings vanishing but an understanding of what they represent is not being passed on to a new generation. Recent studies (Zhang, 2015) highlight the problem of contemporary architects not understanding Siheyuan's tectonic principles and spatial qualities. Although both Chinese and international clients are willing to build and live in Siheyuan housing, due to the fact that most current Chinese architects are not trained systematically to design Siheyuan style housing and the restriction of many commercial factors in practical projects, most contemporary Siheyuan projects are recognized as fakes. The primary cause of this is the complexity of the Siheyuan design theory. The principles of its construction are written in literal text using ancient Chinese language with stick drawings and the principles of room layout and compositional pattern are passed down by craftsmen using pithy formulas, which involve lots of ancient superstitious theories which current architects find difficult to understand. To make matters worse, being timber frame structures, the houses are particularly vulnerable to ageing and problems such as fire, humidity, and pests. During the period from 1949 to 2009, more than 82 per cent of Beijing Siheyuan areas were destroyed (Ni, 2009), to the extent that it was hard to find good examples to study. However, this type of classical dwelling type is still popular today, it is useful to reinterpret its design principles for contemporary architects and students to all the authentic patterns to live on.

Although Siheyuan design principles have been explored in previous studies by Chinese scholars, most of them are focusing on construction, visual aesthetics of decoration, and layout of architectural elements on site using methods of humanities instead of natural science (e.g. Deng, 2004, Jia, 2012, Lv, 2016, Ma, 1999, Zhao, 2013), only a few studies have investigated the Siheyuan design principles as a whole to interpret the entire design process as a whole. However, computational approaches have been applied by western scholars to study Chinese architectural heritage design principles. Stiny (1977, 2006) and his followers (Chiou, 1995, Li, 2001,) employed shape grammar to successfully interpret original design languages of architectural heritage, but they are focused on exploring the computational principles hidden in Chinese style decoration and construction, with an emphasis on finding simple algorithms that could generate complex forms. We are more interested in the possibilities of creating families of forms controlled by a few parameters. Li (2013, 2016), employed algorithms to represent parametric relationships and generate examples of traditional buildings based on a Chinese architectural manual, but those buildings were generic prototypes of single buildings rather than building groups. Most dwelling types of traditional Chinese architecture are, however, groups of buildings or rooms rather than a single building. Algorithmic approaches have not been applied to study design principles of a specified dwelling type in Chinese architecture for the aims of architectural design and education.

This paper explores an algorithm able to generate Siheyuan house variants which respect traditional design principles as used by ancient craftsmen. And it also argues that such algorithms can be implemented in the Grasshopper environment for the use of teaching architectural history knowledge and redesigning Siheyuan. In particular, we are aiming to answer the following research questions:

1. How can the traditional Beijing Siheyuan design principles be translated into parametric algorithms?
2. How can such algorithms contribute to the Siheyuan's efficient three-dimensional representation?
3. How can such algorithms become tools for the utilization of its principles in contemporary Chinese architecture and architectural education?

To answer these questions, Siheyuan traditional design principles from three sources were studied to build design constraints in the forms of an algorithm, which was developed in the Rhino/Grasshopper environment based on visual scripting. In addition, we have discussed the potential applications of the tool in Siheyuan design and education.

MATERIALS AND METHODS

Source of design rules

The conventional approach of Siheyuan design accepted by current Chinese architects and scholars is based on several hypothetical ideal examples that only take into account a proper solution of building orientation, site location, and forms of architectural components on a rectangular site based on classifying the number of courtyards and their combinations (Ma. 1999). This objectivist theory can be criticised because the ideal prototypical Siheyuan is hypothetical, and in fact, lots of historical Siheyuan houses are variants of these ideal examples rather than themselves (Ni 2009, pp136), even though these ideal examples existing only in theory have the potential to be transformed into built variants. Instead, our approach sees Siheyuan as the product of an algorithm based on compositional rules, and we can test it by comparing its outputs with the corpus of built examples. The compositional rules underlying the algorithm are extracted from three main traditional sources:

1. The Fengshui Theory (cloud and water), an ancient Chinese geomancy, provides guidance for selecting a proper building site and efficient architectural construction. Specifically, the verse formula Ba gua qi zheng da you nian (eight hexagrams seven politics big tour calendar) founded on the concept of "cosmic resonance" helps craftsmen and householders predict and select auspicious orientations and qualitative space in the design process.
2. Ancient Chinese buildings were required to follow the construction laws compiled by the government. The Beijing Siheyuan was developed during the Qing dynasty (1616-1912) following the Gongchengzuofazeli (Structural Regulations) compiled by the Qing government.
3. Although ancient governments required householders to follow the construction law strictly, many house variations occurred, based on the experience of the ancient craftsmen passed from each generation to the next.

Analysis of traditional design principles

Understanding the design principles as described in the Gongchengzuofazeli construction manual and passed down by craftsmen is a complicated task since valuable data is mixed with superstitious and feudal hierarchical beliefs. Nevertheless, one can derive three principle design phases, which together cover the entire design process.

The first phase focuses on the layout of architectural elements (single room, veranda, entrance, and walls) and their positioning on the site. There are many factors that shape the layout of architectural elements. In the traditional conventional approach, the first step is to use Fengshui Theory to determine a key point on the site and create a central axis crossing the key point and then determine the auspicious orientations according to the householder's birthday, site context, and site shape. In ideal cases, the orientation of the axis is a little off the north-south orientation. The second step is to determine the Siheyuan entrance. An ideal site is rectangular and orientated north-south with the north-south axis longer than the east-west and the south side connected to a hutong alley, allowing the entrance to be located at the southeast corner of the site. However, in many cases, these ideals cannot be met. Variants of site context and in the orientation of the longer sides of the site, lead to different patterns of entrance location. The most common combinations of these two criteria are illustrated in step two of stage one in Table 1, and corresponding patterns of location of the entrance are given. The third step is to divide the site into courtyards. Ideally, for most Siheyuans, the site is rectangular and there are between one and five courtyards depending on the householder's needs and the site size. The courtyards have their central points juxtaposed along the central axis (parallel grouped

Siheyuan and Siheyuan with garden are infrequent, therefore they are not studied here). The fourth step is to determine the pattern layout of the rooms, the veranda, and the walls in each courtyard. Possible layouts are shown in Figure 2.

The second phase is to determine the form of each architectural element (room, wall, and veranda) that is to decide on its type, and then to calculate its dimensions. Regarding the rooms, there are seven parameters that determine their shape. These are: 1. The number of bays in the front view of the room; 2. The number of rafters in flank sides view of the room; 3. The length of the central bay in the front view of the room; 4. The ratio of two adjacent bays length in the front view of the room; 5. The ratio of the lengths of two adjacent rafters in horizontally projected orientation in flank sides view of the room; 6. The diameter of columns in the outermost row in front-back orientation; 7. Whether or not the room has a front veranda, and whether or not the room has a rear veranda. In practice, the length of the central bay is determined by craftsmen according to the size of the site. These and the value of the other parameters are determined by the ancient construction law and the householder's demands. The veranda's structural form is unique, and its unique parameter is the diameter of its column. The diameter value is determined by the craftsmen's experience based on the site's size. Using the algorithm underlies the craftsmen's mind and the ancient construction law book, forms can be determined and dimensions of them can be calculated. Walls are not parametric but come in several types, such as walls with tiled tops finished in different patterns.

The third phase concludes with locating the architectural elements. Although the location of each architectural element is abstractly given in patterns of layout diagram (rooms are located on the edges of each courtyard, verandas form an enclosed rectangle to connect each room entrance, and walls are located on the section of each courtyard edges that not occupied by rooms), we realized many elements obey this rule loosely. In fact, they can move within the courtyard. However, we always ensure all elements have general bilateral symmetry about the central axis.

These three phases are seen in the division of Table 1 into three parts. This Table summarises the generation of Siheyuan and illustrates that there are seven factors shaping their final form. These are: 1. the householder's birthday; 2. site context; 3. site shape; 4. site size; 5. choice of pattern of architectural elements layout; 6. choice of architectural elements' form and size; and 7. relocation of architectural elements.

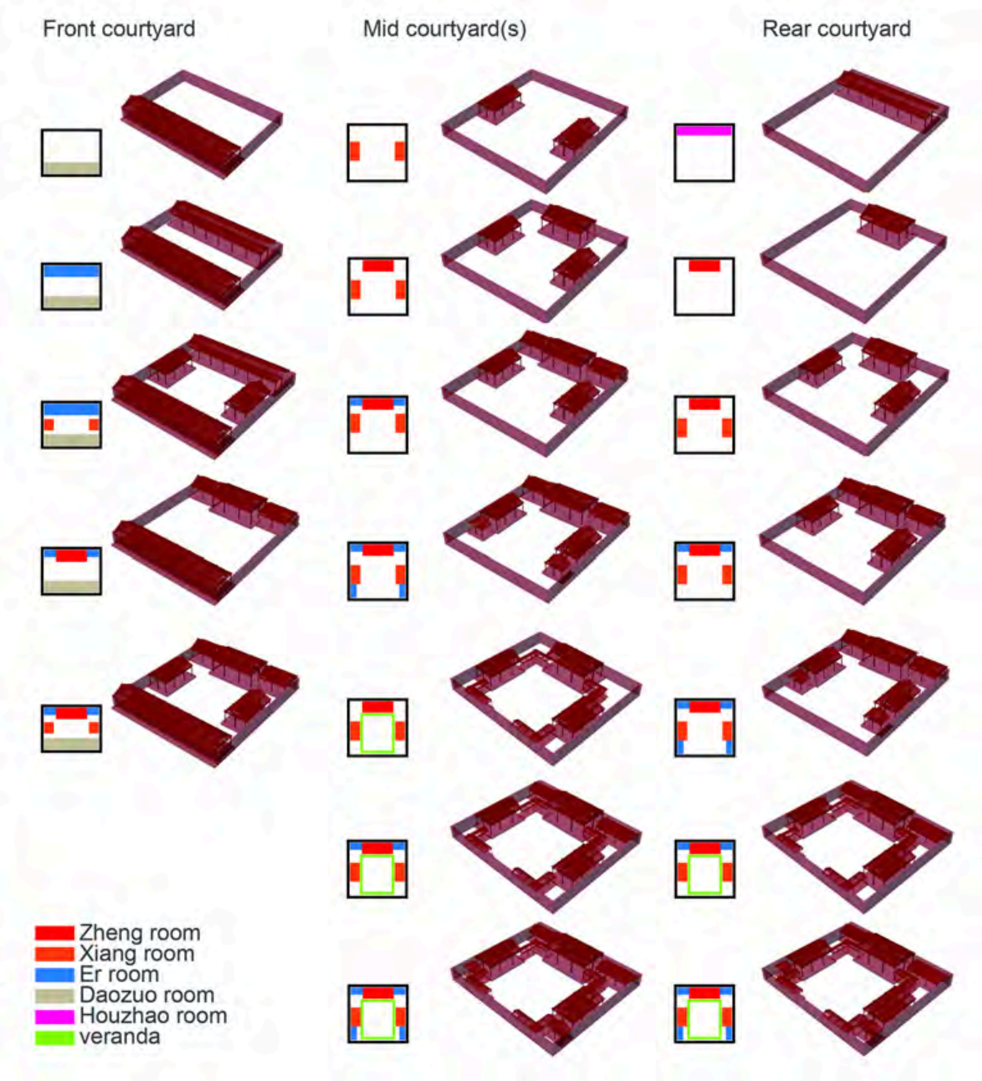
BUILDING OF A PARAMETRIC LOGIC AND COMPUTER IMPLEMENTATION

Based on the analysis of Siheyuan's traditional design principles as described above, we can list the main parameters under the following headings:

1. The site shape, site context, site size, the location of the key point, and the orientation of its central axis,
2. The number of courtyards, the dimensions of each courtyard, the patterns of the layout of its architectural elements of each courtyard,
3. For rooms, the number of the bays in front view of each room, the number of rafters in flank sides view of each room, the length of the central bay in front view of each room, the ratio of two adjacent bays in front view of each room, the ratio of the lengths of two adjacent rafters in horizontally projected orientation in flank sides view of the room, the diameter of columns in outermost row in front-back orientation,
4. Whether the building has a veranda or not, and for that veranda, the diameter its columns,
5. For walls, its pattern, e.g., internal or external walls.

The relationships between the parameters are shown in Figure 3. They formed the input to the visual scripting components in our Rhino/Grasshopper model.

Figure 2
Patterns of the layout of architectural elements



APPLICATION

As the classical dwelling of Beijing in the Qing dynasty, Siheyuan houses are much sought after today. As well as being used for dwellings they can easily be converted into restaurants or hotels or adapted for modern commercial use. Thus, Siheyuan can still be identified as an architectural type in contem-

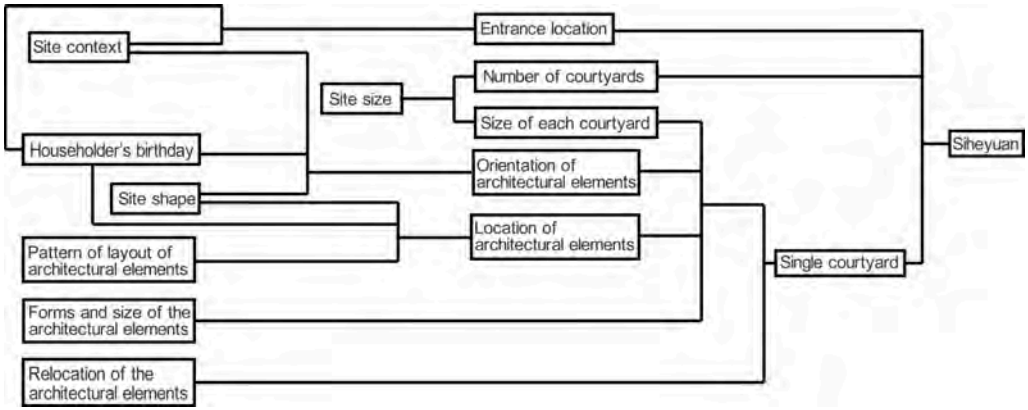


Figure 3
Parametric logic of the algorithm

porary society. Although many superficially similar projects are still being built, people believe they are not authentic unless they follow the original design and construction principles. The algorithm described here, in the form of a Grasshopper script, can, therefore, serve as a tool to both design genuine Siheyuan and explain their design knowledge in a new way.

By using our Grasshopper script and a digital model, virtual Siheyuan can be generated rapidly and efficiently. Previously, in order to design a Siheyuan, architects needed to follow the design principles to determine dimensions of each component before drawing plans and elevations, however, using this tool, architects just need to input the parameters and then the three-dimensional representations will be created automatically. Compared with the conventional method of design and modelling which take many hours, our tool takes only a few seconds to generate models after inputting parameters.

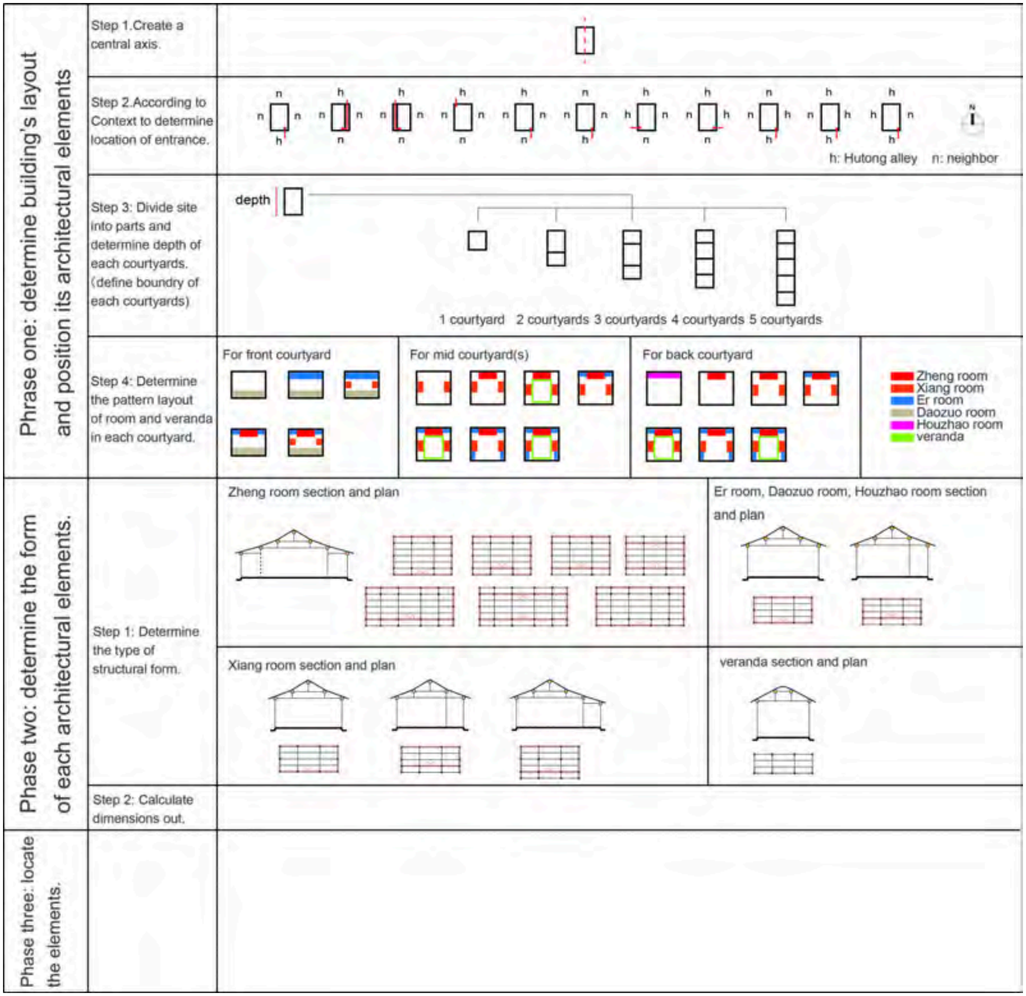
The algorithm can also be used to impart the principles of Siheyuan design. Parametric design is a globally accepted method in architecture, and for many students, the representation of design principles in the form of scripts is easier than to follow the text in the ancient Chinese language with accompanying stick drawings. To test this, we plan to introduce this tool to Xihua University architecture students, who study Siheyuan design principles in an architectural history course, to see if they can look at Siheyuan in a new way, and we will analyze their responses.

Other uses of our algorithms will come from the mass production of virtual historic environments in an architecturally realistic way for use in gaming and documentation of the historic Siheyuan houses by encoding their parameters for use in heritage preservation.

DISCUSSION AND CONCLUSION

The algorithms to parametrically generate Siheyuan are consistent with Fengshui Theory, Gongchengzuofazeli, and craftsmen's experience that works with the constraints of the primary design principles. The script is their implementation in Grasshopper; the three-dimensional representations are digitally built in Rhino when scripting is done. Since the formulated algorithms save time to design for modelling and modifying Siheyuan houses, the tool will be useful to today's architects who wish to work in the Siheyuan idiom. On the other hand, as the Grasshopper algorithm is strictly in correspondence with the original design principles, it can easily illustrate the Siheyuan design knowledge. Rather than having to study the ancient Chinese literal text or verbal pithy formulas, this tool exploits the design

Table 1
The generation process of Siheyuan based on traditional design principles



principles in the form of algorithmic script, which is more understandable for contemporary architects and students. By modifying these sliders of parameters, the impact that each parameter has on the Siheyuan's design can be easily explored. In other words, the knowledge about how principles and factors shape Siheyuan design are demonstrated in a graphic way. That new design experience, in combination with the popularity of the Rhinoceros/-Grasshopper software in architects and students, will contribute to preserve and distribute the Siheyuan design knowledge in a broader audience.

However, the potential of the generated Siheyuan variations by this tool has not been fully explored. First, the model gives only general massing and structural frame, more architectural details, such as constructional joint, have not been incorporated. Adding these parts will be subject to further research. Second, we note there are some extant and disappeared historical examples which cannot be generated by our tool. Our algorithm is based on the hypothesis that craftsmen strictly follow Fengshui Theory to design the layout of architectural components, however, in many cases, since the site is physically restricted by an irregular shape or the household's budget was limited, craftsmen cannot strictly follow these design principles. Therefore, our generated models are representations of ideal examples. Nevertheless, more rules can be embedded in the algorithm, so it will be able to represent more complex and irregular variants. In particular, comparing all generated variants with built precedents recorded on the map Qianlong Jingcheng Quantu (Qianlong Capital Map, 1748-1750), which presents all the buildings of Beijing at a scale of 1: 650, we discovered a few houses, (for instance the house in the square box in Figure 4), that cannot be generated by our tool. What can we make of these outliers? While we are alert to the possibility that there might be more tacit rules than we are aware of, we view these pathological cases as illuminating the normal: since the shapes of sites are usually irregular and there are many other uncertain factors shaping the results, craftsmen often improvised but always tried to be as close as possible to what would occur with no constraint, so that even in irregular circumstances something approximating an ideal form was produced. This explains the common view that Siheyuan is based on an ideal model. We hope, in future work, to use the tool to recreate ancient Beijing as a VR reconstruction of the Qianlong Capital Map, dealing with the few exceptions as special cases. A reconstruction of the ancient capital is thus feasible and may have commercial possibilities in gaming and urban studies. Third, non-existing variants are generated by our tool. When we compared houses produced by our algorithm with surveys of existing houses such as Ma, 1999, Ni, 2009, and Duan, 2016, we found that not all variants developed by our algorithm have in fact ever been built, although we cannot be sure that these surveys cover all types in the real world. We can interpret these discrepancies in two ways. They might represent types yet to be discovered. This is difficult to verify since records of these old houses are rather incomplete. Alternatively, our non-existing Siheyuan variants might indicate that there are hitherto undiscovered constraints, in other words, unknown Siheyuan design rules. For example, it is certain that following Fengshui rules reduces the number of possible forms, and that houses in designed according to Fengshui are preferred, and plan forms that are not in accord with it might be seen as disadvantageous. The study of the relation between what is possible and what actually exists gives us a better understanding of the balance between cultural and physical constraints on architecture.

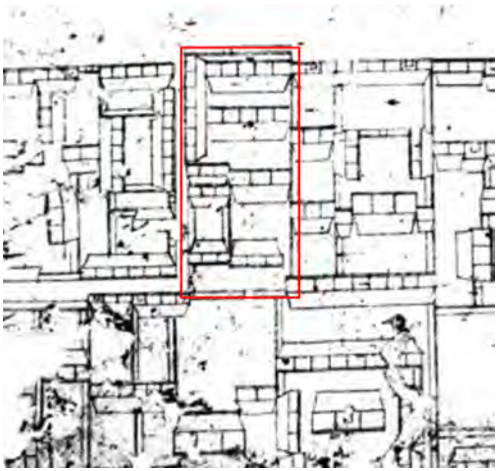


Figure 4
A Siheyuan house in the Qianlong Jingcheng Quantu plan of Beijing that cannot be generated by our algorithm

Meanwhile, the potential of the purposed algorithmic approach to investigate Siheyuan design principles has not been fully explored. Although the original design principles are revealed through our algorithm, the corresponding generated designs are historical ones, of which it is believed the spaces and forms do not adapt to the contemporary way of daily life and aesthetics. However, our algorithm can serve as a starting point to solve the difficulty of designing new Siheyuan houses that both adapt to contemporary architectural function and aesthetics and respect the original design principles and forms. The approach based on shape grammar studies, where original grammars are utilized to create new styles of designs "from scratch" (Duarte, 2005) can be borrowed to re-design Siheyuan by partly modifying our algorithms in order to make the new design solutions adapt to contemporary architecture but not entirely ignoring original principles.

Furthermore, another important finding is that the ratio of dimensions of Siheyuan is constrained by some parameters we have listed above (which figure?). For example, the depth and width of each courtyard plan. By dividing the site into courtyards, since the width of each courtyard has been determined already (the same with site width) and the value of each courtyard depth must be greater than a constant value, the number of courtyards influences the depth of each courtyard, and thus it influences the ratio between the depth and width of each courtyard plan. Based on Duan's measured drawings, we observe that, for most Siheyuan containing more than three courtyards, the ratio between depth and width of front courtyard is 0.2-0.4: 1, however, the ratio of courtyards in the middle is 0.6-1: 1. The reason for this is to create a narrow space as an architectural promenade for guests in front courtyard in order to hide the primary spaces of Siheyuan (usually, they are middle courtyards) but make the primary spaces capacious for hosts (usually, in olden days guests were only admitted to the front courtyard, leaving the main bedrooms and living rooms in middle courtyards for the host), which embodies connotation of traditional Chinese culture, as shown in Figure 5.

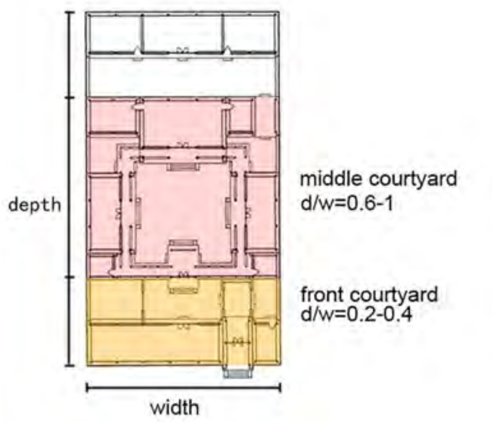


Figure 5
The proportional ratio of the front and middle courtyard dimensions

Finally, we note that the rules for Siheyuan are a way of controlling the standard of buildings, and those rules were applied more rigorously in Beijing than further afield in China. The fact that an algorithmic model of a house is even possible is a reflection of an attempt to control houses by means of rules, which is then reflected in their typology.

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Using Grammars to Trace Architectural Hybridity in American Modernism

The case of William Hajjar single-family house

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In this paper, mid-century modern single-family houses designed by William Hajjar are analyzed through a shape grammar methodology within the context of the traditional architecture of an American college town. A member of the architecture faculty at the Pennsylvania State University, Hajjar was a practitioner in State College, PA, where the University Park campus is located, and an influential figure in the history of architecture in the area. The residential architecture he designed for and built in the area incorporates many of the formal and functional features typical of both modern European architecture and traditional American architecture. Based on a computational methodology, this study offers an investigation into this hybridity phenomenon by exploring Hajjar's architecture in relation to the traditional American architecture prevalent in the college town of State College.

Keywords: *shape grammar, American architecture, William Hajjar, hybridity, college town*

INTRODUCTION

The residential architecture of A. William Hajjar, a member of the architecture faculty at Penn State in the mid-twentieth-century period and a practitioner in the area incorporates many of the shapes and features of both modern European architecture and traditional American architecture-a distinctive quality of his work, which, however, can also be found in the work of his fellow faculty practitioners in other US college towns. A quality, too, that helped popularize modernism in the United States. The present paper is part of a larger-scale study in which this hybridity phenomenon between modernism and traditional American architecture is verified and described using computational methodologies. In this paper, Hajjar's single-family architectural language is analyzed in relation to its specific local context-i.e., the traditional architecture of State College, a typical American college town. On this basis, the architectural significance of Hajjar's work in regard to popularizing/Americanizing a non-popular and imported architectural style is explored. The theoretical outcomes of this study build on the use of shape grammar in verifying and describing the possible hybridity between modern and traditional architecture and more broadly the potential of this tool to describe architectural hybridity in general.

METHODOLOGY

The present paper, as noted, is part of a larger-scale project in which computational design methodology is used to verify and describe hybridity in architectural design with Hajjar's architecture featured as a case study. In the larger-scale project, Hajjar's work is explored via five principal steps: (1) Hajjar's life and practice are traced to identify likely influences on his work; (2) a shape grammar is developed for the houses he designed for and built in State College; (3) the grammars of some of his likely influences are identified or developed; (4) Hajjar's grammar is compared to the grammars of such influences to determine the nature and extent of their impact on his work; and (5) aspects of the social and technological context that may explain such influences are identified-i.e., trends in regard to lifestyle and the availability of materials and technologies.

In previous papers, the authors described Hajjar's single-family architecture in comparison with European architecture and the Bauhaus style through the work of Gropius and Breuer in the United States, whom he met during his architectural studies. This comparison was performed by developing a grammar of Hajjar's work in State College and comparing the rules identified with those of a grammar developed for the Gropius-Breuer partnership in the United States. However, the focus of the current research is on comparing Hajjar's architecture with the traditional American architecture of the context in which his work evolved. The paper includes the rules of a grammar developed for traditional American houses in State College, a derivation of a traditional house in State College (very similar to the traditional house owned by Hajjar in the area), and a comparison of the rules of this grammar with rules of the grammar previously developed for Hajjar's architecture. Two ways to identify similarities between the rules of the two grammars are used: (1) the derivations of houses-with similar layouts-generated by each of the grammars are compared step by step, and (2) plans for a traditional house constructed in the area-with a common interior layout similar to those generated by the grammars-are produced through both the grammar of traditional architecture and the grammar for Hajjar's architecture, and then compared with each other.

SHAPE GRAMMAR

Introduced by Stiny and Gips in 1972, the concept of shape grammar in computation is defined as a class of production systems based on an initial shape (or a set of finite shapes) and transformational rules that can be applied to the original shape recursively. This method has been used to analyze examples of historical architecture, such as the Palladian villas (Stiny & Mitchell, 1978), Frank Lloyd Wright's Prairie houses (Koning & Elizenberg, 1981), bungalow houses (Downing & Flemming, 1981), Queen Anne houses (Flemming, 1987), and Alvaro Siza's houses at Malagueira (Duarte, 2005).

In the past three decades, using the concept of shape grammar, several scholars have studied the notion of stylistic evolution and introduced the idea of grammatical transformation. This scholarship includes Knight's seminal work on the transformation of Wright's Prairie houses into Usonian houses (1983), Çolakoğlu's contemporary houses based on vernacular Turkish Hayat houses (2005), Chase and Ahmad's account of hybridity in design (2005), Eloy and Duarte's adaptation of existing house types to meet contemporary needs (2011), Kruger, Duarte, and Coutinho's study of Alberti's influence on classical Portuguese architecture (2011), and Benrós's (2018) study of the phenomenon of hybridity in architectural languages. Extending the research cited, the present paper is principally concerned with using shape grammar to describe the influence of traditional American architecture on Hajjar's single-family architecture in the context of a central Pennsylvania college town.

WILLIAM HAJJAR

Abraham William Hajjar (1917-2000) studied architecture at the Carnegie Institute (now Carnegie Mellon) (1936-1940) and the Massachusetts Institute of Technology (MIT) (1940-1941) and served as both a faculty member at the Pennsylvania State University (Penn State) and a practitioner in the area in the mid-twentieth-century period (1946-1963). While Hajjar was a student at the Carnegie Institute, most of the architecture faculty, like the majority of U.S. architecture programs, favored the Beaux-Arts philosophy of design. Yet, some young faculty members, especially during the late 1930s, who were assigned to teach freshman and sophomore studios favored International Style architecture. At the invitation of these faculty members, Walter Gropius, as the new director of Harvard's architecture program, gave a lecture at Carnegie Mellon in March 11, 1938, while Hajjar was a sophomore there.

At Carnegie, the students were doing ink drawings with washes of classic Greek columns, and as a result, Hajjar became interested in this genre such that he produced ink and watercolor renderings for most of the projects he designed in the following years. However, he became well-versed in modernism at MIT, especially while working under the supervision of Lawrence Anderson, who not only designed the first modernist building on an American campus (the MIT Alumni Pool, 1939) but also endeavored to bring a modern outlook to MIT's program in the late 1930s. While Hajjar was at MIT, Gropius and Breuer were invited regularly-mostly by Anderson-to deliver lectures there and to participate in student work reviews. Not only Hajjar, but also his classmates, learned about the Bauhaus style of modern architecture through these interactions with some of the pioneers of modern architecture.

After receiving his Master of Architecture degree from MIT in 1941, Hajjar initially joined the State College of Washington as a faculty member. In 1946, however, he joined the architecture faculty at Penn State. When Hajjar moved to State College with his family, most of the single-family houses in the area were in the Georgian revival, Colonial revival, Tudor, and Cape Cod styles, although ranch and split-level houses were starting to appear. Similar to other

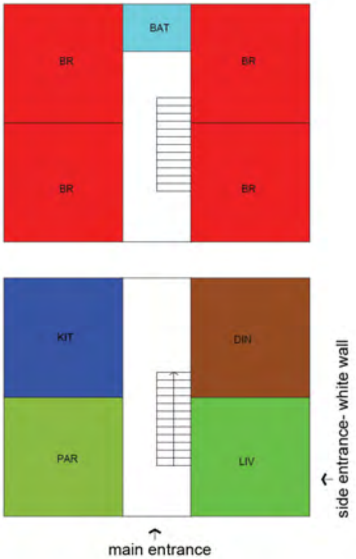

Figure 1
Hajjar's first house in the area and its schematic layout.

houses in the area, the first home that Hajjar bought for his family in the area was a Georgian revival house with a traditional four-square organization (Figure 1). His first project in the area was a house he designed for his own family in 1951-1952. This project was successful enough to attract local clients, many of whom were Penn State faculty members. In fact, Hajjar designed and built a total of thirty-three houses in the area. Many of his houses blend with the traditional houses in the neighborhood in terms of exterior building materials, volumes, and roof shapes. However, Hajjar's houses have an internal organizational structure that is both modern for the time and unique to his work.

THE COLLEGE TOWN: AN AMERICAN PHENOMENON

The college town, in its instantiation as an American phenomenon, is a community that is heavily dependent on the university it hosts (Brockliss, 2000). College towns have characteristics in common both with small towns and with cities: for example, in terms of population, urban setting, and most of the infrastructure, they are comparable to other kinds of small towns. However, in terms of culture and education, they are more comparable to cities. It is important to note, though, that colleges differ from each other in terms of size, mission, fields of study and degrees offered, entrance requirements, tuition costs, etc., and, therefore, attract students and faculty who reflect those differences and who, in turn, "shape the character of the towns in which they are located" (Gumprecht, 2008, p. 22).

The idea of university life and of the university community, as Laurence Brockliss argues, does not have its origins in the U.S., but in the medieval European universities where students and teachers lived, worked, and studied together in a "cloistered environment" (2000). Yet, the comprehensive planned modern university campus, or what Thomas Jefferson called the "Academical Village," is primarily an American phenomenon (Chapman, 2006). Beginning in the colonial period, American colleges followed the English "collegiate" model; even the large universities developed in the United States initially followed this model. Although they followed many English precedents, American colleges developed their own "American" character. For example, unlike in the European/English model, which favored separate colleges in separate locations within a town, colleges in the US were clustered together to create a campus, some of which were built in downtown city areas. However, as another innovation, or another break from European tradition, most campuses in the US were built in separate communities or towns in the countryside or even in the wilderness (Turner, 1984).

Modern houses in college towns, especially in neighborhoods near the universities, are usually the result of a specific set of conditions: for example, it was observed in a study of Urbana, IL, that professors were more likely to own or construct houses that were architecturally distinctive than to buy ordinary houses-as a way to set themselves apart as an educated class (Gumprecht, 2008). Furthermore, general awareness of modern movements through an architecture program might be another important condition in towns where people are likely to be very connected socially. This is in addition to the direct relationships between the architects and the clients, the latter of whom were also faculty members in some cases. Most college towns have at least one older neighborhood near campus that is home to a large number of professors. The College Heights Historic District in State College, PA, where nearly half of the houses Hajjar designed in the area are located, is an example of this kind of neighborhood.

TRADITIONAL AMERICAN ARCHITECTURE IN STATE COLLEGE, PA

In A Field Guide to American Houses, Virginia and Lee McAlester designated houses found in typical American neighborhoods as either "folk houses" or "styled houses." Folk houses or vernacular houses are built usually by the occupants or other nonprofessional builders without any specific intention of following current fashion. However, as the researchers state, most American houses surviving from the 19th century are not folk houses but styled houses, which were built with "at least some attempt at being fashionable" (McAlester & McAlester, 2009 p. 5). The styles described in their book comprise Colonial houses (1600-1820) Romantic houses or revival houses (1820-1880), Victorian houses (1860-1900), Eclectic houses (1880-1940), and houses since 1940 (including contemporary and neo-eclectic). As noted, McAlester and McAlester based their stylistic approaches, descriptions, and style categories on domestic architecture found in typical American neighborhoods throughout the country. The present study, however, focuses on traditional American houses in State College, PA, with the goal of uncovering their architectural influences and analyzing how the latter relate to Hajjar's mid-twentieth century architecture.

Located in central Pennsylvania, State College is a college town dominated both economically and demographically by the University Park campus of the Pennsylvania State University (Penn State). Evolving from a village to serve the needs of the Pennsylvania State College (founded as the Farmers' High School of Pennsylvania in 1855), State College was incorporated as a borough in 1896. Expanding with the growth of the university, neighborhoods adjacent to the University Park campus started to be developed mostly in the early twentieth century. To study single-family domestic architecture designed in traditional styles in the area, it is instructive to explore the College Heights Historic District, a national historic district located north of campus that was added to the National Register of Historic Places in 1995 (National Register Information System). As stated in the National Park Service's registration form, College Heights encompasses land and historic buildings associated with the early residential history of the town and "represents its growth and architectural development as an emerging college town" (p. 2). All historic districts, including College Heights, consists of "contributing" and "non-contributing" properties. The registration form for the College Heights district indicates that there are 278 contributing properties in this area. Although all the contributing houses have a special characteristic(s) in relation to the history of the neighborhood, the registration document highlights some properties as best examples of houses designed by local architects/contractors or popular mail-order catalogues (Table 1). Most of these examples, constructed in the 1920s and 1930s, are built in bungalow, colonial (Dutch and Georgian), colonial revival, Georgian revival, and four-square styles. Figure 2 shows examples of the contributing houses in the College Heights Historic District. Of these architectural styles, two interior plans are particularly popular in the neighborhood: a four-square organization and a four-room organization with a hallway in the center, very similar to Hajjar's first house in the area. Figure 3 shows examples of each kind of interior organization.

Figure 2
Examples of traditional houses in the College Heights Historic District.

Address	Style	Date	Architect
214 Hartswick Ave	Craftsman bungalow	1920	Unknown
117 East Park Ave	Craftsman bungalow	1923	Unknown
326 West Ridge Ave	Dutch colonial	1920	Unknown
329 West Ridge Ave	Dutch colonial	1921	Unknown
722 Holmes Street	Georgian colonial	1935	Clarence M. Bauchspies
629 Sunset Road	Georgian colonial	c. 1935	Clarence M. Bauchspies
525 West Park Ave	English Tudor	1931	P. Boyd Kapp
525 McKee Street	Colonial revival	c. 1932	P. Boyd Kapp
172 Hartswick Ave	Mission style	c. 1921	Unknown
333 Arbor Way	Tudor	1935–1936	Kapp & Kennedy
705 McKee Street	Colonial revival	c. 1931	Unknown
711 McKee Street	Colonial revival	c. 1931	Unknown
154 Ridge Ave	Tudor revival	1928	Frederick Disque
714 McKee Street	Colonial revival	1931	Walter Trainer
311, 317, 323, 327 East Park Ave	Colonial revival	c. 1933	Clarence M. Bauchspies
625 Holmes Street	Colonial revival	c. 1933	Clarence M. Bauchspies
721 Holmes Street	Tudor revival	1933	Clarence M. Bauchspies
608 Sunset Road	English Tudor	c. 1935	Clarence M. Bauchspies
629 Sunset Road	Georgian revival	1935	Clarence M. Bauchspies
346 Ridge Ave	Colonial revival	c. 1934	Clarence M. Bauchspies
615 N. Burrowes	Colonial revival	c. 1935	John Breneman
235 West Ridge	Tudor revival	c. 1935	John Breneman
705 N Holmes Street	Tudor revival	c. 1937	Carl Wild
426 W Ridge Ave	Tudor revival	c. 1935	John Frises
326 W Ridge Ave	Four-square	1920	Mail order
243 West Park Ave	Four-square	1925	Mail order
210 Hartswick Ave	Four-square	1929	Mail order
217 West Park Ave	Half-timbered	c. 1925	Mail order
214 Hartswick Ave	Bungalow	c. 1925	Mail order-Sears
143 West Park Ave	Bungalow	c. 1925	Sears Westly
520 Holmes Street	Bungalow	c. 1922	Sears Westly
215 Ridge Ave	Dutch colonial	1922	Arthur Cowell
433 Mitchell Ave	Tudor cottage	c. 1928	Unknown
747 Holmes Street	Cape Cod	c. 1938	Mail order
320 Hartswick Ave	Colonial revival	1932	Cont: Albert Bartges/Sears

Table 1
Examples of Traditional American Houses designated as Contributing to the College Heights Historic District.

Figure 3
Main floors of a typical mail-order plan with a center hall colonial organization (left) and a four-square organization (right).

GRAMMAR FOR TRADITIONAL AMERICAN HOUSES

The grammar presented in this paper is introduced as a grammar for traditional American houses, although it is specifically a grammar for traditional American houses in the College Heights Historic District. The corpus of designs includes the houses noted in the previous section (Table 1). Interior organization was the main feature considered in the process of analysis, with an emphasis on the two most popular interior plans in the area: the four-square and the four-room organization with a central hallway. Given the popularity of these plans, this emphasis is appropriate. However, there is also another key reason: this interior organization underlies most of Hajjar's designs. Additionally, as many of the houses in the district are bungalows, the grammar developed for this kind of house in Buffalo, NY, by Downing and Flemming (1981) was also considered in the development of the grammar presented herein. Although Downing and Flemming developed their grammar for houses in Buffalo, NY, as most of the houses in their corpus were catalogue homes similar to bungalow houses in State College, it is rational to use their rules in developing a grammar for traditional houses in the State College area. Especially given that many of the bungalow houses built in both cities were constructed during the same period (1920s) from the same design source (Sears).

It is important to note that only grammars developed with the same strategy, for example, additive or subtractive, can be compared accurately. Therefore, in some cases, it was necessary to slightly modify the rules of the Buffalo bungalow grammar in order to relate it to the grammar for traditional American houses in State College (College Heights district) and also to the grammar for Hajjar's architecture (Figure 4). An important similarity between the grammar for the bungalows and the grammar previously developed for Hajjar's single-family architecture (Hadighi & Duarte, 2018) is that both grammars start from the overall inhabitable space and then proceed to the allocation of spaces based on public and private functions. Of course, allocation of spaces or the way in which the larger spaces are divided into smaller spaces or rooms is strongly dependent on

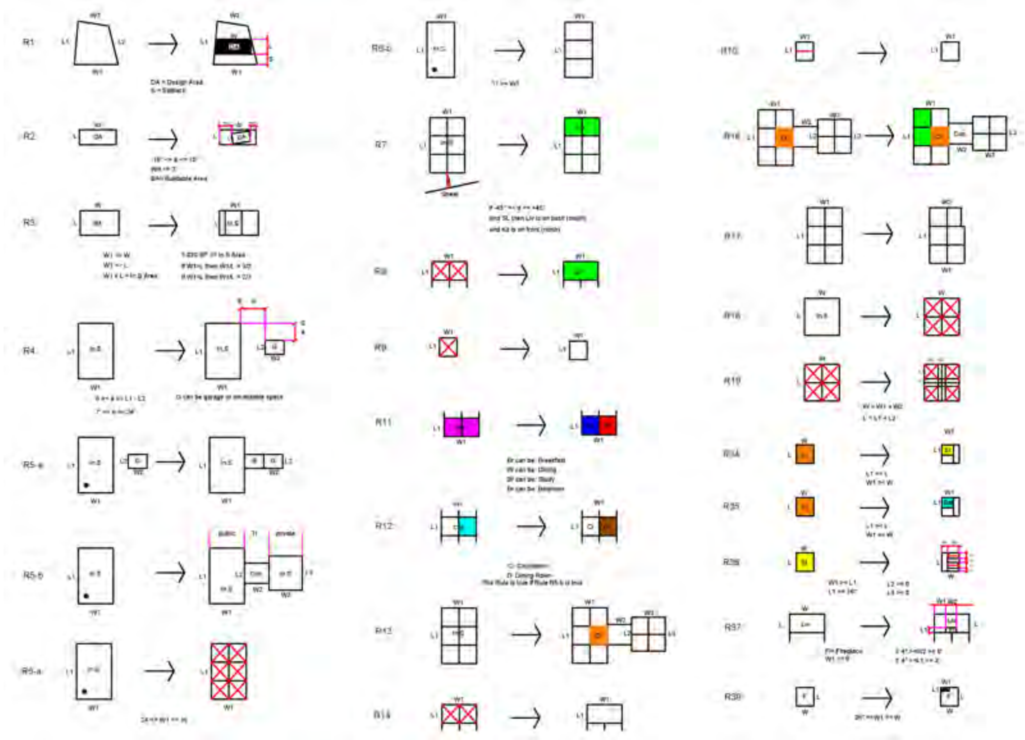

Figure 4
Selected rules of
Hajar's grammar

both the technological and cultural aspects of the context: for example, the maximum width of a room is a dependent variable of maximum beam spam and the spatial flow or openness of the living room, dining room, and kitchen is very much related to prevailing notions of privacy in domestic life.

Similar to the grammar of the Buffalo bungalows, in Hajjar's grammar the inhabitable space can be divided into six (or four) functional spaces/rooms. In Hajjar's grammar, any of the "rooms," particularly the middle ones, can be divided into smaller spaces to create small hallways or stairways, or service areas, such as a bathroom or furnace room. On the other hand, in the grammar for the bungalows (like the grammar developed for the traditional houses) additional spaces were introduced between two "rooms" to create stairways or service areas. (Figure 5).

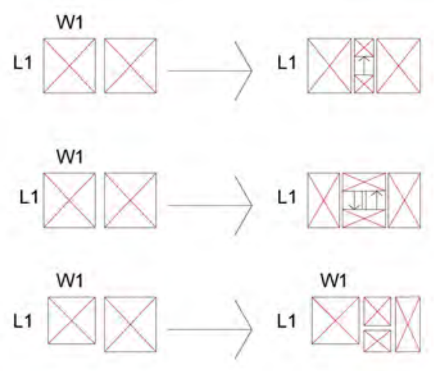

Figure 5
Rules to allocate staircase, bathroom, and halls adapted from the grammar for Buffalo bungalows (Downing & Flemming, 1981).

Based on the houses in the corpus and the rules adapted from the grammar for the Buffalo bungalows, a grammar was developed for traditional American houses in the State College area. Similar to the grammar for Hajjar's single-family houses, the grammar for traditional American houses encompasses different groups of rules: rules to define the overall inhabitable space; rules to describe the way in which interior space is divided into smaller spaces or rooms; rules to allocate the interior functions; and rules to generate details such as the placement of closets, the placement of a fireplace, and wall thickness. Selected rules of the grammar developed for traditional houses in the area are shown in Figure 6.

Figure 7 shows the derivation of a design in the corpus used to infer the grammar. The design is related to a house built in the colonial revival (neo-Georgian) style in the College Heights Historic District. It is very similar to the first house Hajjar bought in the area for his family. In an effort to compare the two grammars-the grammar for Hajjar's single-family houses and the grammar for traditional American houses-Hajjar grammar is used to derive a design solution with a fairly similar interior organization as the house in figure 7 (Figure 8). It is interesting to compare the two design solutions, one the result of the traditional grammar, actually a house built in the area, and the other a house produced by the grammar of Hajjar's work that is as close as possible to that traditional house (with the same geometry and the same idea of interior organization. The main differences between the two solutions are: (1) the placement of the main entrance door, which in the plan produced by Hajjar's grammar is at the side of the house instead of the dead center front; (2) the flow of spaces, which in the plan produced by Hajjar's grammar results in a very open floor plan; (3) the placement of the living area, which in the plan produced by Hajjar's grammar is at the back of the house facing the backyard. It is important to note that Hajjar generally designed his houses in a different orientation: the houses that he designed in the area commonly-though not always-have their longer side perpendicular to the street. Hajjar's houses in the area either have a square-shaped plan divided into four smaller squares (and nine squares in his second family house) or a rectangular shape divided into six smaller spaces. Figure 9 shows the step-by-step derivation (based on Hajjar's grammar) of a house built to Hajjar's design in 1959 in the area with a square-shaped plan and an interior allocation of spaces very similar to that of the colonial revival house generated by the grammars (Figure 7).

In general, it is evident that the geometry of Hajjar's designs is similar to that of other houses in the

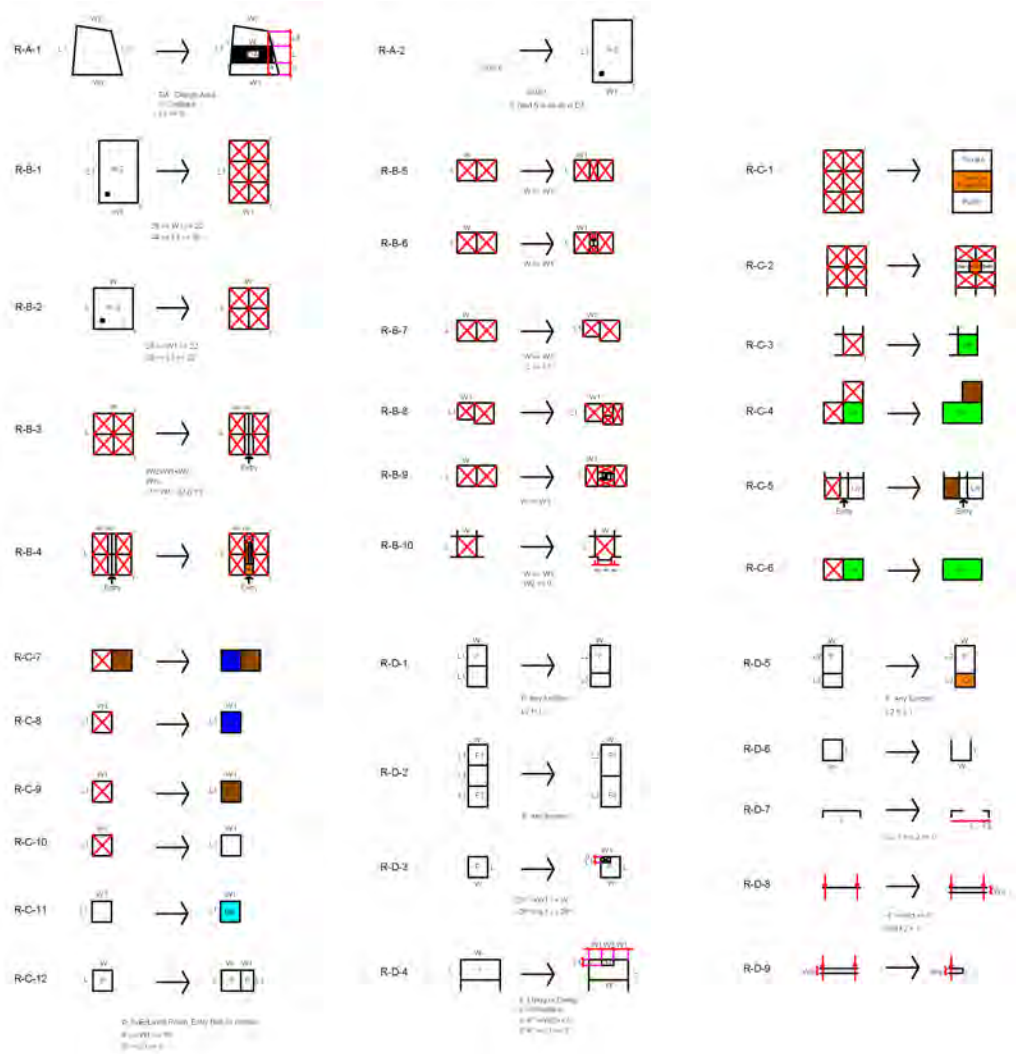

Figure 6
Selected rules of the generic grammar for traditional houses in the State College area.

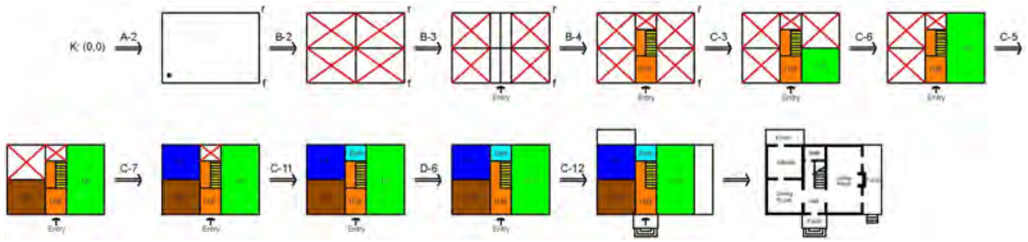

Figure 7
Derivation of a traditional house based on the generic grammar for traditional houses in the area.

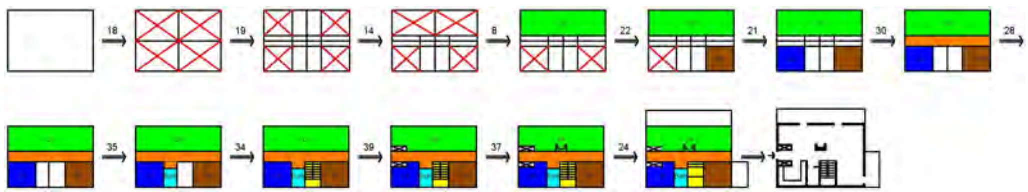

Figure 8
Derivation of the same traditional house shown in figure 7 based on Hajjar grammar.

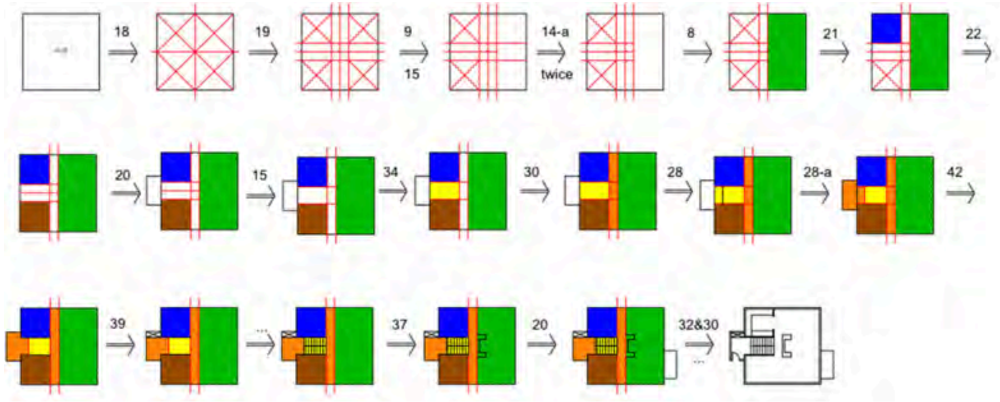

Figure 9
Derivation of the Snowdon House, designed by Hajjar in 1959 based on Hajjar grammar.

area. Also, the division of the main inhabitable space into smaller spaces/rooms in Hajjar's designs is very similar to that of the traditional houses in area. Hajjar's allocation of interior functions also shows similarities with the traditional architecture in terms of the flow of spaces. However, the flow of spaces and openness of his interior planning, and his attention to the idea of energy efficiency-for example by placing the fireplace not on an exterior wall, but as a main design aspect of the interior circulation distinguishes his architecture, all of which lean toward modern principles of design. In fact, these are all design elements that Hajjar learned from Anderson, his master at MIT, and through interacting with Gropius and Breuer and studying their architecture. This hybridity between European modernism and American traditional architecture was a key to Hajjar's success in practicing architecture at an American college town in the mid-twentieth century. A hybridity that helped popularize modern architecture in the area at that time. Of course, changes in people's lifestyles and the cultural and socio-economical changes after World War II in the United States led to a reassessment of the principles of residential architecture in the country-a need to which contractors and architects responded nationwide.

CONTRIBUTIONS

The purpose of the proposed study is to highlight the effectiveness of shape grammar as a computational tool for analyzing hybridity in architectural design and comparing styles with each other. In relation to Hajjar's architecture in the State College area, this study highlights his contribution to the stability and popularity of modern architecture in the United States by mixing the forms and functional features of modern European architecture with traditional American architecture to create an architectural "style" that may be unique to American college towns and that can be understood as a localized, Americanized, college town modernism. This idea needs to be more explored and further developed in future papers. The grammar of Hajjar's houses is presented in previous research (Hadighi & Duarte, 2018). Here, the grammar for traditional American houses is presented and then used to determine the extent to which Hajjar's houses are similar to traditional American houses in the area.

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Calculating Movement

An Agent Based Modeling System for Historical Studies

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Simulating human movement and actions in historical spaces/landscapes is a complex task. It requires not only the recreation of spaces that no longer exist, but more challenging the recovery of actions performed in the past. These actions can provide insights into important aspects such as how people inhabited, used, perceived, lived, sensed, and shaped these spaces. This research aims to show a framework to approach studying human movement, using an Agent Based Modeling (ABM) system. Our ABM tool has methods for creating, managing, and choreographing the movement of agents through 3D models. A number of iterative tests, both agent-to-agent and agent-to-model, enable the system to produce scholarly quantitative data in historical spaces. We highlight the use of this system through two case studies, one at an architectural scale and the other at landscape scale.

Keywords: *Agent Based Modeling, Art and Architectural History, Simulation*

INTRODUCTION

This paper reports on the development of a system incorporating agent-based modeling (ABM) in art/architecture historical research and scholarship. ABM is a computational process simulating agents' movement, behaviors; the relationships between agents; and the interaction between agents and their environments (Wurzer, 2015). ABM has been used in a range of fields including predicting the spread of epidemics, behaviour in economic systems, movement within the built environment, egress modeling (e.g. stadiums, submarines) and many more (Axtell, 2002; Bandini, 2004; Hamil, 2005; Lynne, 2015; Macal, 2005; Simeone, 2012).

In art/architecture historical research, ABM enables working with both formal space and the inhabitants within. Agents are modeled on human behaviour to navigate and "sense" their environment, both architectural and landscape, and programmed with basic rules for autonomous decision making. This approach can expand both art historical questions and narratives by observing emergent movement in space, interactions between inhabitants, and interactions between inhabitants and the built environment. As an iterative computational process, ABM allows for experimentation exploring emergent outcomes from variations in agent rules.

The two case studies, Istanbul Toptaşı Insane Asylum and St. James Way at San Julián de Samos, demonstrate how ABM can be applied to varied research questions. The spaces studied can be specific structures with highly ordered interior spaces, as in the first case study, or large scale landscape topographies with many different components, as in the second case study. Through the occupation of agents within 3D models, we show how this technique can be applied as a method of research and inquiry building upon established historical spatial studies.

THE ABM SYSTEM

OVERVIEW

Our ABM system functions within the Unity application. The system is provided through C Sharp scripts, prefabricated objects, and a user interface (UI) canvas all created to extend the base functionality of Unity. A series of discrete C Sharp scripted components create, populate, control, and test the agents within imported 3D models. Generation and movement of agents is managed through external text files, allowing for the efficient study of different agent configurations and movements. Agent testing data can be observed first hand within the system as well as saved out of the system into external Comma Separated Value (CSV) files for data processing and visualization.

AGENT CREATION AND DEFINITION

Agents are defined as instances of a single prefabricated template agent (Figure 1). This template consists of simple 3D geometry providing a visual identifier, a location for agent behaviour scripts, and the navigation behaviour component. By instantiating a single agent template, system-wide updates to the agent geometry and scripted agent logic are centralized in a single location. Upon creation, every agent is added to a master list that is used to coordinate all system to agent communication. This master list allows any component (clock, testing, navigation, csv output) within the ABM system to broadcast information to all agents efficiently without knowing the specific name or location of each agent.

Figure 1
Agent Template
Unity Prefab.

Agents may be instantiated one of two ways in our system. If single or small numbers of agents are needed, they may be added manually through UI button based controls. The ABM system includes a geometric object identified as the “spawning location,” which determines where in the 3D model these new agents will be created. This object may be manually relocated as needed for alternative agent locations. A single click to the “Create Agent” button in the UI instantiates a single new agent at this location.

If large numbers are needed, the system provides an efficient method for defining agent cohorts. In this case, a natural language external text file can be written outside of Unity defining the agents. This file is ingested into Unity and programmatically instantiates the agents within the system, using a number of predefined attributes for the group. These attributes determine the number of agents, their qualities and states, their designated “home” location, and a number of identifiers employed in agent-to-agent and agent-to-model testing. Additionally, the specific movement of each agent in the cohort is supplied a set of time:location pairs that prescribe agent movement during the 24 hour clock. This external text file adheres to the JSON format to allow for easy automated reading into the ABM system.

By generating the agents from an external file, rather than a “hard coded” definition within a script, our system is flexible, allowing iterative experiments that operate at different time spans or spatial scales/-formations. For instance determining large numbers of agents arranged within architectural spaces or agents moving through spaces in specific daily or ritual routines. A outline example of this file format is included below.

{
“Type”: “Agent Type”,
“ID”: “Agent Unique Identification Code”,
“Sex”: “Male/Female”,
“State”: “Agent State”,
“Total_Number”: Integer,
HomeObject”: ”Object Name”,
“Color”: “Color Name”,
“Itinerary”: {
“time1”:“location1”,
“time2”:“location2”,
“time3”:“location3”,
“time4”:“location4”,
“time5”: “location5”
}}

The “Type”, “Sex”, “State”, “Total_Number”, “HomeObject”, and “Color” parameters allow classification of agent cohorts. The “Itinerary” component determines the movement of the agents through time:location triggers. The “Itinerary” component can hold as many triggers as needed to provide complex scripted movement throughout a simulation.

AGENT NAVIGATION

The movement of agents through 3D models utilizes existing Unity navigation tools. Prior to starting the simulation, individual or multiple 3D model objects are defined as either navigable or obstacles to navigation. Navigability is determined based on slope, step height and clear distance between obstructions. For example, topography, paths/roads, floors, ground and staircases are defined as navigable surfaces with appropriate step heights and slopes. Walls, columns, closed doors and closed architectural models are defined as obstructions. Unity references these definitions to build a master navigable mesh (NavMesh) of relatively low resolution that is used by the agents for path finding and movement (Figure 2).

The agent template is predefined with a “NavMesh Agent” component allowing Unity to move each agent freely and autonomously on the NavMesh. Our system uses this component to issue commands directing each agent to Start, Stop, or Redirect themselves throughout the simulation.

The NavMesh Agent component requires specific target coordinates for choreographing movement. Unity combines the target location, NavMesh object and any NavMesh obstructions to determine the path each agent will follow to their current target. Within our system agents may have targets assigned both manually through UI buttons and automatically assigned as the “location” object in the JSON file “time:location” pairs. For instance, a JSON file including “1330:Main_Courtyard” in the “Itinerary” component will automatically assign the NavMesh target location of the “Main_Courtyard” object at 1330 (130pm). In both cases the system assigns target coordinates based on the location of the specific geometric object referenced as target.

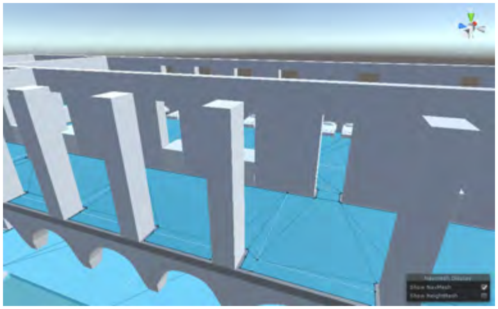

Figure 2
NavMesh component visible on a 3D architectural model surface in Unity.

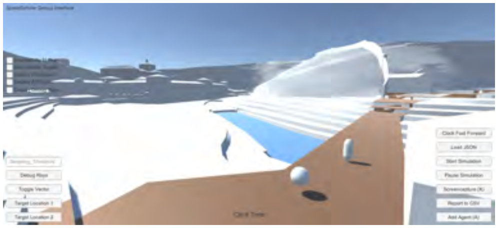

Figure 3
Agent (capsule) approaching NavMesh target (sphere).

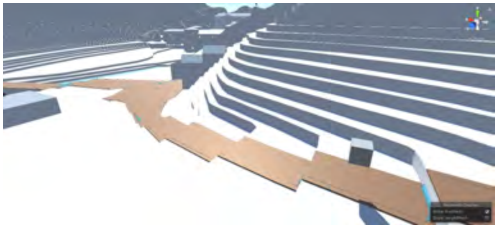

Figure 4
3D topographical model surface in Unity.

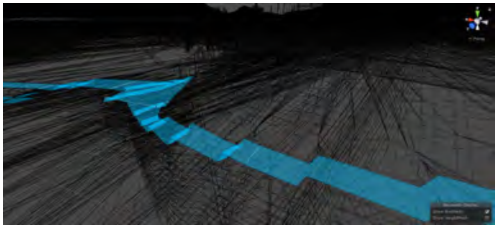

Figure 5
NavMesh on the 3D topographical model surface in Unity.

AGENT SEQUENCING, TIMING AND COORDINATION
A single clock script calibrated to count on a 24 hour cycle coordinates all movement within our system. When the clock reaches a predefined increment, set to each minute by default, the clock broadcasts the current time to each agent in the master list. Scripted logic within each agent evaluates the clock time received with the internal agent itinerary. If there is a corresponding itinerary command keyed to this time the agent moves accordingly. This logic allows the master clock to efficiently keep simulation time, while having each agent autonomously manage its movement.

AGENT TESTING
A number of tests may be run within our ABM system. Several of the tests include time intensive computational calculations determining visibility and collisions using highly accurate raycasts between objects. To overcome this inefficiency, test scheduling and frequency are managed interactively through the master clock. By increasing or decreasing the frequency of these tests our system can balance efficiency and accuracy for specific scholarly needs. Following are some tests available in our system.

AGENT TO AGENT INTERVISIBILITY AND DISTANCE
Agents test for intervisibility between themselves and all other agents within the simulation. A raycast is sent from the agent individually towards another agent and any resulting collision is tested to be an agent or a non agent geometry. In the case of a positive agent collision information detailing which agent was seen and how far the distance was at that moment.

AGENT TO 3D MODEL INTERVISIBILITY
Agents test for visibility of a specific component in the 3D model which is subdivided into a 3D grid. Each grid point is tested for visibility through a raycast from the agent. The agent tests positive collisions to determine if the component was seen.

PERCENTAGE OF MODEL OBJECT IN VIEW
Agents test the percentage of visibility for a 3D model component within their field of view. Through the use of a camera, the agent renders a view in the direction of their movement including the target model component rendered in a full red color (255, 0, 0 in 24 bit RGB color space). This rendered image is stored in a “render texture” and each pixel is tested for its color value. The number of full red pixels, resulting from the presence of the model component in view, is then divided by the overall number of pixels within the frame to determine percentage in view.

AGENT DATA PROCESSING
The results of agent tests are time stamped by the clock and stored individually and locally by each agent. A CSV file can be written out of Unity through a script to the local file system with the test result data from all agents. This CSV file facilitates external data processing and visualization to gain insights from the ABM simulations.

CASE STUDIES
This ABM system has been applied to two specific case studies: the Istanbul Toptaşı Insane Asylum (Is-

tanbul, Turkey) and the St. James Way at San Julián de Samos (Samos, Spain). Both of these historical sites were transformed over time in their architectural space, their physical compound and, as a result, the actions taken within. Next, we will see how the use of this ABM system allows us to populate these historical spaces, to simulate past actions in them, and to research issues difficult to approach with traditional spatial analysis techniques.

ISTANBUL TOPTASI INSANE ASYLUM

The first case study is the Istanbul Toptaşı Insane Asylum (functioned 1876-1924). What makes this project interesting in terms of art/architecture historical questions is the fact that it is not a purpose-built asylum. In other words, the building itself is not necessarily a masterpiece in its genre, and, accordingly, its significance does not manifest itself formally as it would in a more conventional art historical approach. The significance in terms of Ottoman modernization and medical modernization as embodied in architecture becomes apparent when one tracks the changes the Asylum went through (e.g. construction, building additions) and the way the building was reprogrammed by a specific reorganization of time and space.

Based on scattered evidence on life in the asylum and the scripted schedules, we model itineraries for both patient and physician agents. These itineraries prescribe the movement of agents through their 24-hour daily routine. Through these choreographed movements of agents throughout the day, we observe the interactions between various cohorts of patient and physician. Iterative computational tests assess the exposure of patients to each other, natural light, air, and ventilation. The asylum presents a productive case study of applying ABM to art/architectural history as the specific movement of agents emerges from, and provides insight into the medicalization of preexisting space within a converted medical facility. For the scope of this case study, we focused our ABM research on the Women's Section within the larger asylum.

The first step was to create a 3D model of the asylum. Based on historic documents, drawing, site surveys, and photographs of the structure,we constructed a schematic 3D model of the buildings and immediate surroundings. This 3D model included all floors, staircases and ground surfaces for navigation and all walls, doors and columns for navigation obstructions. The patient wards were populated with 3D models of beds arranged and numbered according to both historical drawings and textual records of the asylum population (Figure 6).

Patient wards held at times thirty to forty patients in residence, each assigned to a specific bed. In order to effectively populate each ward at the start of simulation, we developed the system to ingest external JSON files to automate agent creation. A scripted function assigns each patient agent created by the JSON to a unique bed automatically, simplifying the locating of all agents within the asylum. The itinerary for each patient orchestrates their movement through the asylum based on a strict daily routine gathered from archival documents. Patients start the day at their bed and move through the day between their assigned ward, dining halls for meals, courtyards for "airing" and back their bed in the ward for physician daily rounds (Figure 7). Below is an example of a Toptasi patient agent definition file.

```
{
"Type": "Patient",
"Block": "E",
"Ward": "1",
"ID": "Auto",
"Sex": "Female",
"State": "BedRest",
"Total_Number": 29,
"HomeObject": "TestWard1_Home_Array",
"Color": "White",
"Itinerary": {
"745": "Target DiningHall 2",
"855": "Home",
"1045": "Target DiningHall 2",
"1145": "Target Courtyard",
"1401": "Home",
```

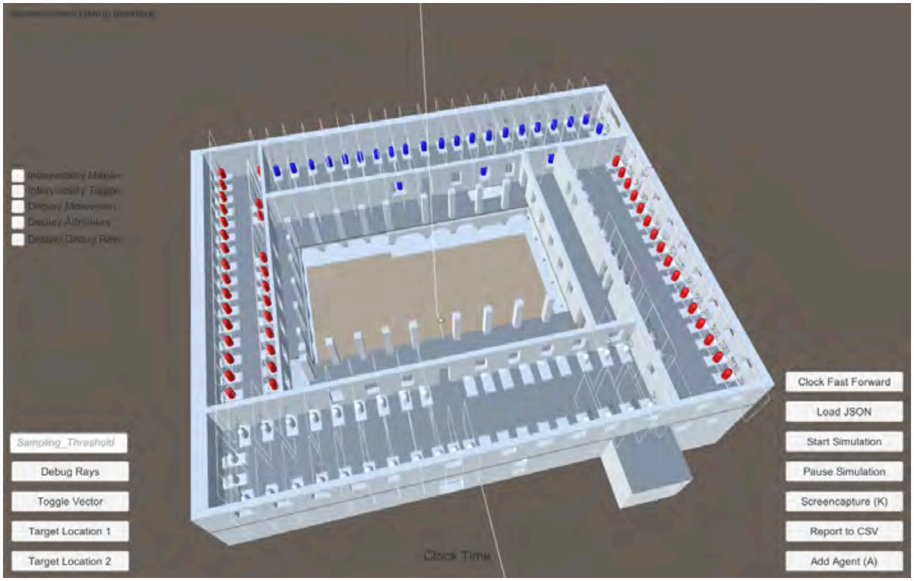

Figure 6
Toptasi Asylum Women's Ward fully populated with agents from four external JSON files.

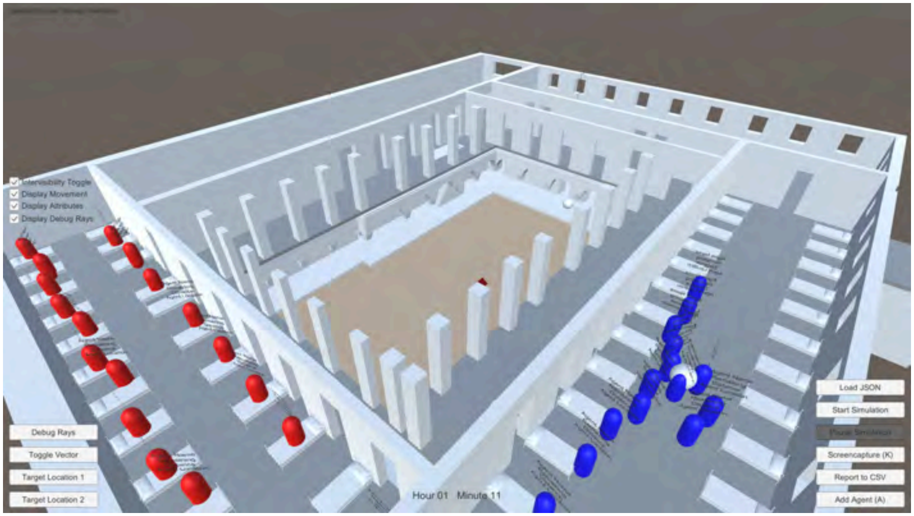

Figure 7
Toptasi Asylum Patient Agents moving through their daily routine.

```
"1545": "Target DiningHall 2",
"1705": "Target Courtyard",
"1811": "Home"
}}
```

The "Itinerary" component determines the movement of the agent(s) while the fields above (Type, Sex, State, etc) allow classification of agent cohorts. Some of the classification fields (Block, Ward) are coordinated with the metadata schema of the SpatioScholar system (Wendell 2016).

The main objective of the ABM simulation at this stage is analyzing whether or not the scripted rules of daily life in the asylum could be implemented given the number and types of admitted patients in the year 1911. Multiple agent definition files are used to fully populate the four wards with each patient assigned a bed. Physicians are created through additional scripts and cycled through the wards for the daily patient visits. The simulation charts the course of movement of both patient and physician agents over a prescribed 24 hour daily cycle.

We developed the Agent-to-Agent-Intervisibility test to determine which agents are visible to each other throughout the 24-hour daily cycle in the asylum. This test regularly evaluates each agent in the system against all others for positive intervisibility. When the test is successful, meaning the two agents have a line of sight connection, the results are stored by the initiating agent with a timestamp from the 24-hour cycle. This test allows us to iterate specific scenarios of patient populations in each ward and daily routines to gain insight into the contact between patients from different wards and between patients and physicians. This agent to agent contact may shed light on the impact of ward assignments and daily medical routine of patients.

THE ST. JAMES WAY AT SAN JULIÁN DE SAMOS

The second case study analyzes the visual experience of pilgrims along the way to Santiago de Compostela at a specific location and period in history. The location is the monastic site of San Julián de Samos, in Galicia (Spain). We examine this historical landscape in the early 19th century, prior to secularization.

Based on archival documentation, we know that the monastic site at that period comprised a church, two cloisters, a kitchen, the Chapel of the Cypress and other independent buildings for cattle, storage, milling, and so on. Moreover, a large piece of land around the monastery was enclosed by a wall to separate the sacred space from the outer world. Additionally, there was a small village towards the south, not far from the monastery, but properly separate. In this compound, the way towards Santiago de Compostela surrounded the monastic precinct on the east side, running through the adjacent rural area, and crossing the village.

While this historical physical realm is not currently extant, it was a built environment in the pilgrims' journey at this period in history. By using the ABM system, we aim to better understand the pilgrims' visual perception of this monastic site in the early 19th century. The system will allow us to start questioning if the fact of being seen or not seen had an influence in the way that the monastic site was conceived and organized by the monks.

The first step was to build a 3D model of the monastic compound at the specific period in question. This model is based on previous long-term research where this historical site was studied over the course of several centuries of continuous change. Within this research each stage of the monastic sites evolution was visualized in a 3D model. For the present work, we used the 3D model corresponding to the early 19th century. This model recreates the elements of the monastic site; the monastic buildings, the sacred enclosed precinct and the wall, the nearby village, the immediate territory and the topography.

The second step was to use the ABM system to simulate the pilgrims' movement along the way. The existing 3D model of the site was brought into Unity and incorporated into a scene including the ABM system objects and scripts. The specific navigable path along the topography had been modeled as an individual 3D component. This path was selected and

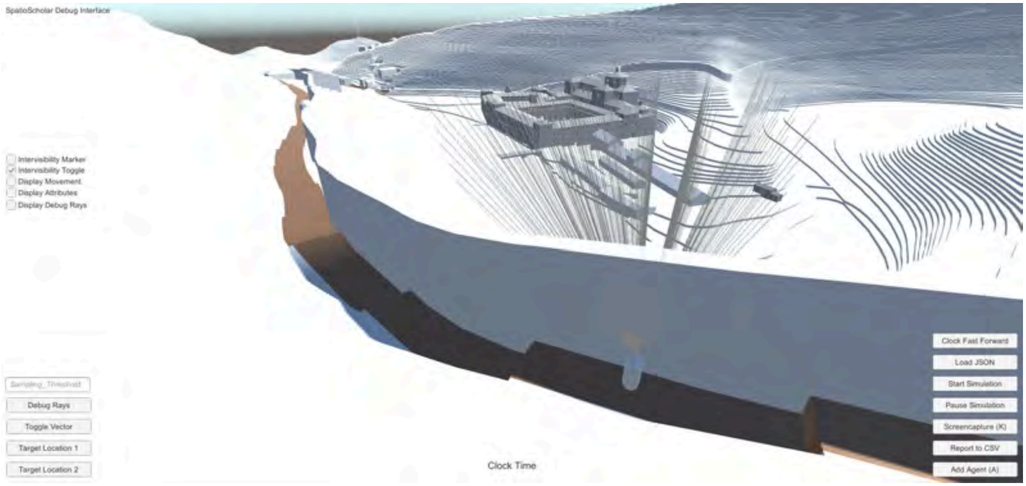

Figure 8
Agent testing intervisibility towards the Samos Monastery.

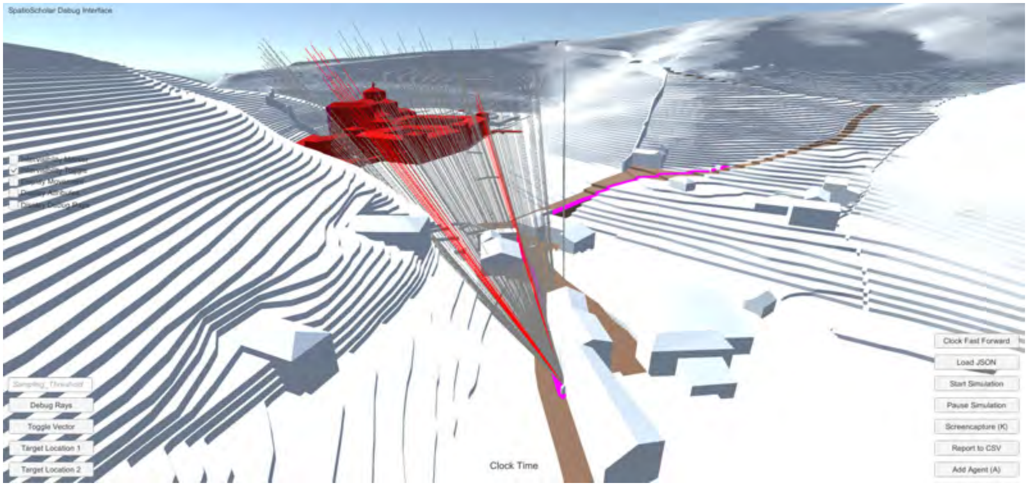

Figure 9
Agent successfully creating intervisibility tests from the village to the Samos Monastery.

turned into a "NavMesh" object with widely lenient navigation controls. The "spawning location" object was placed at one extreme end of the path and a target location object was placed at the other extreme end. The location of these objects insured that agents would travel from one end of the modeled path to the other without interruption.

The 3D model components of the monastic compound were assigned as "Intervisibility Target" objects in Unity and we implemented the Agent to 3D Model Intervisibility test to evaluate the visibility of these objects by a single agent as it moved along the path. To determine if the monastery was visible, each monastic compound object was subdivided into a volumetric grid. At each step along the path the agent drew a raycast from itself to each grid point and tested if a successful intersection was achieved with the monastery. If the surrounding wall or topography was seen, or if no 3D model was in view the test was false. If the monastery was intersected by the raycast it was recolored with a red material to visually indicate intervisibility. In addition, a script on the agent would draw a line object upon the topography underneath to record a geographic marker of the intervisibility. By using a small number of subdivisions in the volumetric model sampling this test could be run quickly with less accuracy, potentially missing out on architectural features and forms in the raycast function; by increasing the number of subdivisions the test could be run less efficiently with a higher accuracy.

This ABM testing allowed us to gather specific quantitative data describing the visual relationship between the monastery, as it existed prior to secularization, and the pilgrim along the way. A large wall segregating a large quantity of the monastic grounds was determined to play a significant role in framing the views of the monastic property. Understanding the specifics of how this controlled the views and framed the passage of the pilgrims had opened new inquiries into both the larger geographic relationship of the wall to the outlying hamlets and the immediate geography between the monastery and the village where a high degree of visibility was found.

CONCLUSIONS

In historical art/architectural studies, spatial occupants have often been excluded from research due to the challenges of incorporating them into existing methods. ABM systems such as the one documented in this paper provide new opportunities to simulate occupants in a research oriented framework. ABM studies can generate insights into the movement through and sensing within these spaces. These insights extend the research into historical spaces, opening lines of inquiry focused on the sensing of the inhabitants and how that explores the use, functioning, programming, changing and development of space.

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Church Heritage Multimedia Presentation

Case study of the iconostasis as the characteristic art and architectural element of the Christian Orthodox churches

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This paper is part of ongoing research which aims is to develop the methodology for the church heritage digitization and visualization. The subject of the presented work is the iconostasis, as a significant part of the Christian Orthodox church heritage, distinguished by its bilateral character, as an architectural element of a church interior and an art piece composed of icons. Considering that iconostases can be seen only in situ, we developed the methodology for its digitization and virtual representation dissemination, which provides a user with the possibility to visualize iconostases outside the physical borders of sacral interiors. The proposed methodology relies on techniques for photogrammetric surveying, 3D modeling, and augmented reality visualization, and it is presented in a particular case study of the iconostasis. An outcome is shown as the multimedia presentation of an exhibition, realized throughout collaboration between the university and the museum.

Keywords: *church heritage, iconostasis, multimedia presentation, photogrammetry, AR*

INTRODUCTION

In terms of modern technologies, a virtual representation of cultural heritage has the major and an essential role for the purposes of preservation, conservation, as well as a promotion of tradition and national identity, in the context of globalization. 3D reconstruction methods for digital preservation of cultural heritage, such as photogrammetry, have become increasingly used as a low-cost method for documenting and analyzing of cultural heritage. According to the plenty researches and case studies that use photogrammetric approaches, the main subjects of cultural heritage digitization can be classified by the type of cultural heritage as: archeological sites (Böhler and Marbs 2004; Sapirstein 2016); architectural objects (Yastikli 2007; Nagakura et al. 2015; Webb et al. 2016; Böhler and Marbs 2004); statues and sculptures (Böhler and Marbs 2004; Heinz 2002; Pieraccini et al. 2001); and museum artefacts (Nicolae et al. 2014; Böhler and Marbs 2004).

This research focuses on church heritage digitization and visualization. In particular, the subject of the paper is the iconostasis as a distinctive element of the cultural heritage of the Christians, distinguished by its bilateral character, as an architectural element and an art piece composed of the religious paintings.

The iconostasis is one of the most notable features of the interior of the Orthodox and Eastern Christian churches, characterized by the specific artistic, architectural, visual and theological significance. As a characteristic art piece, it represents a richly decorated vertical frame (solid screen) composed of the religious paintings (icons). As an architectural element which dominates the interior of the Orthodox churches, it serves as a visual as well as the physical division between the sanctuary containing the altar area and the nave in a church. By the theology meaning, it separates the layman in the nave from the priest in the sanctuary (Melvani 1981) and represents the symbol of the division between holy and profane, heaven and earth, divine and human (Fanny 2017).

This work presents the workflow which aims to create a museum multimedia presentation of the iconostasis, as the specific art and architectural element of the cultural heritage of the Christian Orthodox churches. It is an outcome of the university and the museum collaboration.

Since the iconostases present unique elements of the monumental interior, and as such can be seen only in situ, the multimedia presentation is significant as it bridges physical gaps and provides a user with the possibility to visualize one of the most valuable cultural heritage of Orthodox Christians outside the physical sacral interiors. For that purpose, the virtual representation of the iconostasis is created by using photogrammetric methods for surveying and 3D modeling. Since the iconostasis can be simultaneously considered as an altar barrier in a church interior, as well as the screen of the religious art paintings, different photogrammetric approaches for surveying are required. An outcome of the surveying, 3D modeling and visualizing of the iconostasis is shown as the multimedia presentation of the museum paintings exhibition.

CASE STUDY OF THE ICONOSTASIS AS THE CHARACTERISTIC ART AND ARCHITECTURAL ELEMENT OF THE CHRISTIAN ORTHODOX CHURCHES

Iconostases initially evolved from the low altar barrier with an architrave, known as a Byzantine templon (Melvani 1981; Fanny 2017). High iconostases, in the form of solid screens with large icons, are developed in Russia in the late 14th and 15th centuries and probably spread thence to Mount Athos, and further to Greece and the Balkans (Fanny 2017). In the 18th century, iconostases became the most decorative elements of the Christian Orthodox churches, with the highly decorated carvings and icons, made by the most influential artists of that time.

The subject of this research is the iconostasis located in the Serbian Orthodox Church of St. Procopius the Great Martyr situated in a village Srpska Crnja, in central-east Banat, alongside the border with Romania, which dates from the period of the 18th-19th century. Besides its religious value, it is also the significant cultural heritage of Serbia since contains rear sacral paintings of the Georgije “Đura” Jakšić (1832-1878), one of the most expressive representatives of the 19th-century Serbian art. The first large painting commission that young Đura Jakšić received involved replacing and copying the icons on the iconostasis in the Church of St. Procopius the Great Martyr in Srpska Crnja. He painted eight icons of the iconostasis during 1853 and 1854: the central icon of the iconostasis, four throne icons, icons on the Royal Doors, and on the North and South Door (see numbered icons in figure 1a).

As opposed to the most of objects of cultural heritage that have a distinctly organic and three-dimensional shape, the iconostasis is characterized by a notable flat shape distinguished by ornamental decoration and materialization. Except the icons surrounded with the highly decorated frame, other important elements of the iconostasis are richly carved doors: one located in the center and known as a Royal Door, and two on each side, called Deacon's Doors (see figure 1).

Besides the primary architectural function as an altar barrier that separates the altar apse from the nave in a church, iconostases also hold the rare and unique works of artists in the field of sacral painting. As such, iconostases can be also considered as the museum art pieces.

METHODOLOGY

This research focuses on the multimedia presentation of the iconostasis. According to that, a methodology for the 3D digitization and visualization of the iconostasis, as the specific part of the church heritage, is created. The methodology for the iconostasis digitizing and visualization is designed considering three main parameters:

- the iconostasis shape and the size,
- church interior conditions,
- 3D model application.

The methodology is based on the few main steps:

1. Iconostasis surveying;
2. Data processing;
3. 3D modeling;
4. 3D visualizing.

Considering the large dimensions of the iconostasis, situated inside a constrained church interior, the main challenge was to achieve iconostasis 3D representation by using a photogrammetric approach. The proposed photogrammetric approach arises from the specific bilateral character of the iconostasis, as well as from its large dimensions and a flat, yet complex shape. Since it can be considered as an architectural element and the museum art piece composed of the religious paintings, as well, a complete 3D reconstruction with detailed texture was required. Thereby, one of the main parameters that were taken into account during designing the methodology was the required level of detail of the iconostasis 3D model visualization, needed for further application. The result of the proposed methodology for the iconostasis digitization is shown as the multimedia presentation of the museum paintings exhibition in the Gallery of Matica Srpska ([1];[2]) in Novi Sad, Serbia. The museum multimedia presentation consists of two different types of iconostasis visualization:

1. Augmented reality (AR) application for a total 3D representation of the whole iconostasis;
2. Web application which allows a detailed 3D representation of part of the iconostasis that contains icons painted by Đura Jakšić, as well as the high-resolution visualization of the images of that particular icons.

This paper presents the designed methodology for the 3D digitization and visualization applied to the particular iconostasis of the Church of St. Procopius the Great Martyr in Srpska Crnja. However, on the basis of the detailed study of the surveying parameters related to the iconostasis structure and dimensions, its position inside the church, and a characteristic location conditions of church interiors, as the main parameters that affected image-based modeling approach, we propose the methodology that can be repeated the same in the similar surveying scenarios of other iconostases, with changing only a few parameters of the surveying process, according to a specific case study.

Iconostasis surveying

Taking into consideration the bilateral character of the iconostasis and its ornamental shape, as well as its specific position in the church interior, the surveying is split into two main workflows:

1. Total 3D representation of the iconostasis;
2. Detailed 3D representation of single iconostasis elements, such as icons, framed with a gilded carving, and the doors.

Two pipelines based on *SfM* (structure from motion) photogrammetric method for surveying are designed. Each of two main workflows relies on two different *GSD* (ground sample distance) values, initially determined in order to achieve the desired level of detail of the iconostasis reconstruction. Ground sample distance is the distance between adjacent pixel centers measured on the ground, and as such it presents pixel size expressed in an object scale.

First, we determined surveying parameters mutual for both workflows. Due to the notable flat nature of the iconostasis structure, distinguished by significantly lower object depth in relation to its width, the photos were taken in a parallel fashion. In order to introduce detailed iconostasis depth into the 3D model, the parallel mode is combined with divergent camera locations, rotated in the right and left direction by the angle of approximately 10°. The complete iconostasis surveying is performed using the tripod and the camera NIKON D7000 (pixel number: 4928x3275; pixel size: 4.78µm; sensor size: 23.6x15.6mm; focal length: 18-109mm). In order to measure a proper exposure, based on the church interior lighting condition, characterized by a very low illumination, the *Aperture priority* mode is employed to determine correct exposure time, while the values *f-stop* = f/8 and the default *ISO speed* = 100 were manually fixed. The value *shutter speed* = 1 second, selected by the camera as the most suitable exposure time, is fixed and used throughout the whole project. This way, the internal camera parameters, based on the church interior conditions were determined for both workflows.

Figure 1
a) Scheme of the iconostasis in the Orthodox Church of St. Procopius the Great Martyr in Srpska Crnja (author: Vladimir Petrović, The Provincial Institute for the Protection of Cultural Monuments, Petrovaradin, Republic of Serbia); Icons painted by Đura Jakšić: the central icon of the iconostasis (1), four throne icons (2,4,6,8), icons on the Royal Doors (5a,5b), and on the North and South Door (3,7); b) the iconostasis; c) the Royal Door; d) the framed icons of the Royal Door

The second part of the surveying planning is related to the geometric, as well as the location characteristics of the iconostasis. As the typical architectural element of the Orthodox church interiors, the iconostasis is positioned in between an altar apse, behind it, and the church chancel, in front of it. The chancel area includes the side choirs, which slightly occlude the iconostasis on both sides, while the unconstrained space in front of the iconostasis stretches 11m in length to the western main entrance. The iconostasis dimensions of 6,64 (width) x 6,41 (height) meters mainly follow the width and the height of the church.

Since the camera position in relation to the object is not restricted in terms of the limited distance, we designed a methodological approach which depends on the desired level of detail of the representation. In order to achieve different levels of detail of the iconostasis 3D representation, we determined desired *GSD* values: in the range of 0.6-0.8mm for the detailed 3D representation, and 0.9-1,1mm for the total 3D representation, accordingly.

Detailed 3D representation. In this case, the first and the second floor of the iconostasis consisted of the Royal door and gilded carving frames which hold the icons painted by Đura Jakšić were surveyed separately, according to the previously obtained camera parameters, orientation and the position relative to each of them. In order to achieve surveying of the full height of one floor in one stripe of photographs, we used wide angle lens with the 24mm focal length (*c*). By setting the value *GSD*=0,6mm, the distance (*D*) covered on the iconostasis with photograph is determined by considering a particular camera pixel number (formula 1).

$$D = \text{pixel number} \cdot GSD \quad (1)$$

Accordingly, the distance (*D*) is calculated as follows: $4928 \cdot 0,6 = 2,956mm = 2,9m$ (portrait mode); $3275 \cdot 0,6 = 1965mm = 1,9m$ (landscape mode), where the pixel number corresponds to 4928x3275. Since the obtained value of 2,9m covers the first-floor height (2,5m), the appropriate camera orientation resulted in the portrait mode. Further, values for the scale (*m*), as well as the distance from the camera to the object (*h*), are calculated in the following way (formula 2 and 3):

$$m = GSD/\text{pixel size} \quad (2)$$

$$h = m \cdot c \quad (3)$$

The scale (*m*) was $0,6/4,78 = 0,1255 \cdot 10^{-3}$, and the distance from the camera to the object (*h*) resulted in $0,1255 \cdot 10^{-3} \cdot 24 \Rightarrow h = 3m$, where the focal length (*c*) is 24mm. The survey of the first iconostasis floor is carried considering the constant distance of 3m and the baseline (*b*) of 0,3m providing an average overlapping of 80% between photographs.

The same methodology is applied to the second iconostasis floor surveying scenario, since, in this case, the camera was oriented at a certain angle in order to fully cover by photographs the second-floor height. This resulted in the predefined value of the distance of the camera to the object (*h1*), which was expressed as the mean value of shorter and longer distance hypotenuse (see figure 2). According to this, first, the scale is calculated (see formula 3) as: $m = h/c = 3500/24 = 1,458 \Rightarrow GSD = 0,7mm$, obtaining the *GSD* value which is appropriate for the given scale, and consistent with the initially determined range of values.

The third floor was not surveyed separately since it does not contain the particular icons of the painter, so the detailed reconstruction was not required. However, since it stands on the height of 3,95m, for its detailed representation, the drone should be employed.

Total 3D representation. For the total 3D reconstruction, the iconostasis is surveyed in two stripes, using the *GSD* value initially set in the range of 0,9-1,1mm. Setting the value *GSD*=0,9mm, the first stripe of photographs had covered the first and the second-floor height simultaneously. The same way, the second stripe had covered the second and the third floor, obtaining the *GSD* of 1,1mm, due to the certain angle of the camera position. The same methodology for the surveying parameters calculations, used for the detailed 3D representation is performed. Figure 2 illustrates the surveying processes, created for both scenarios.

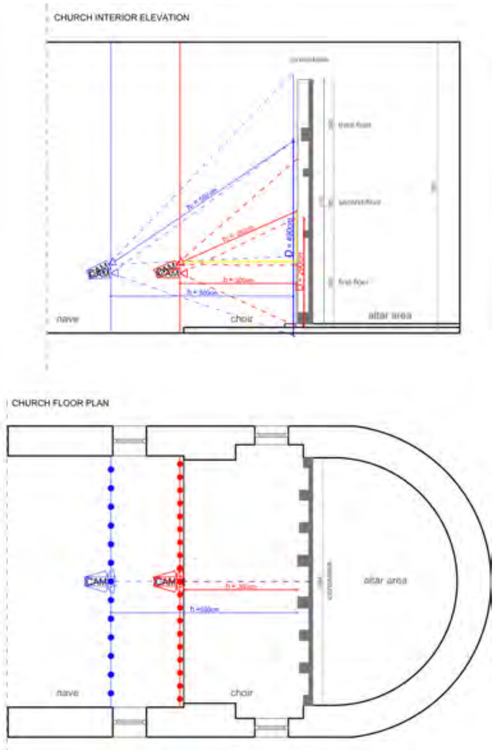

Figure 2
Scheme of the surveying process, created for both scenarios (red line - detailed 3D representation; blue line - total 3D representation)

By taking into consideration the particular distances from the object and the fixed aperture, the depth of field (*DoF*) is checked for every single case, with the aim to achieve a correct sharpness of the photographs. In the case of the detailed 3D representation surveying scenario, the nearest distance of the camera to the object was 3m and the far limit was 4m, so we first checked the *DoF* for the focus of 3m distance. Since for the *f/8* and the distance of the 3m, *DoF* is 1,64m at near limit, and 17,3m at the far, (15,7m in total), so the focus in front of the subject is 9%, the nearest distance of the 3m was used as the appropriate camera focus point. For the total 3D representation surveying scenario (nearest distance to the object = 5m; the far limit = 5,8m), the camera was focused at the subject distance of 5m, which covers the depth of field of 2m in front of the iconostasis, up to infinite behind it. The calculated parameters for two different surveying scenarios are shown in table 1.

Data processing

Data processing was done using automatic, photogrammetric software, based on the depth map method, which generates mesh directly with depth map data, allowing a reconstruction of exceptionally detailed geometry.

The photographs acquired by each of the surveying scenarios were processed separately in order to estimate error and the reconstruction accuracies (see table 2). In addition, the stripes of images were linked and processed mutually, creating two different 3D models. The detailed 3D representation consisted of the particular icons painted by Đura Jakšić, is created by simultaneously processing photographs related to the first and the second iconostasis floor. The total 3D representation of the iconostasis is based on the mutual processing two stripes of photographs of the linked first and the second floor, and the second and the third floor, respectively.

By studying the specific church interior conditions, as well as the iconostasis structure and its characteristic position inside the church, we designed a methodological approach which depends on the desired level of detail of the reconstruction. The proposed methodology is evaluated by comparing the *GSD* value resulted by processing data with the one initially established for each of the surveying scenarios, individually, as well as in their compatible combination. The achieved accuracies and the reconstruction parameters, resulted by using high-quality processing settings are shown in table 2. For the total 3D reconstruction the masks were applied to the photographs, which reduced the number of points and polygons. It can be concluded, that re-

Table 1
Surveying parameters for detailed and total 3D iconostasis representation surveying scenarios: D = distance covered by photograph; h = distance of the camera to the object; b = baseline.

Surveying parameters	Detailed 3D representation		Total 3D representation	
	1st floor	2st floor	1st + 2st floor	2st + 3rd floor
focal length (c)	24 mm	24 mm	24 mm	24 mm
GSD	0,6 mm	0,7 mm	0,9 mm	1 mm
D	2,9 m	2,9 m	4,9 m	4,9 m
h	3 m	3,5 m	5 m	5,5 m
b	0,35 m	0,35 m	0,50 m	0,50 m
focus point	3 m	3 m	5 m	5 m

Table 2
Estimated error and the achieved accuracies and reconstruction parameters, resulted by using high-quality processing settings

Data processing	Detailed 3D representation		Total 3D representation		
	1st floor	2st floor	1st + 2st floor	2st + 3rd floor	1st + 2st floor + 2st + 3rd floor
GSD (mm)	0,59	0,85	0,90	1,16	0,95
Mean error (mm)	0,082	0,024	0,018	0,024	0,039
Depth maps	58	37	48	23	71
Dense points	24,858,174	4,074,637	10,669,166	8,358,967	10,837,310
Polygon count	1,120,750	273,331	978,557	832,972	1,601,083

gardless of the height of the iconostasis (6,5m), the ground photogrammetry provides satisfying results in two different levels of details. Figure 3 shows the orthophoto obtained after detailed 3D reconstruction. Total 3D representation of the iconostasis obtained by using the proposed methodology and automatic photogrammetric approach is illustrated in figure 4a. Considering that the data processing results are consistent with the previously determined surveying parameters, it can be concluded that the same methodology could be adapted to a number of similar iconostasis surveying scenarios, which is the subject of the future research.

3D modeling

The meshes are automatically created by the generating mesh from depth maps tool in photogrammetric software, providing a high level of detail (see figure 4a). According to the needs of the further 3D model application, the mesh is additionally edited using a few different digital tools. Software for digital sculpting is used with the aim to improve the 3D model, in terms of editing geometry, cleaning redundant faces and closing holes (see figure 4b). In order to prepare the 3D model for its visualization in the augmented reality environment, the mesh polygon count is optimized by performing retopology techniques. Given that the iconostasis is composed of the religious paintings, notable attention is dedicated to detailed texturing. Since the poor lighting conditions of the church interior caused uneven exposure between images, as well as an overexposure on side photo areas, the photographs, taken in *RAW* format were manually edited prior to the automatic texture generation inside the photogrammetric software. The image exposure was manually improved by exposure correction toolset in a photo editing application. Furthermore, the texture was un-

Figure 3
Orthophoto of the detailed iconostasis 3D representation

Figure 4
Total 3D representation of the iconostases: a) automatically generated 3D model; b) improved 3D model; c) unwrapped texture map

wrapped and exported into 3D texture painting software, whereas the specular and normal maps, were created, in order to refine the visual quality of the iconostasis 3D model material appearances (see figure 4c).

3D visualizing
3D models with additional options and information are visualized throughout the virtual environment made for the museum exhibition of paintings. The 3D visualization of the iconostasis can be split into two main parts:

1. Augmented reality (AR) visualization of the whole iconostasis;
2. Web application which allows detailed 3D model visualization of the linked first and the second iconostasis floors, consisting of particular framed icons painted by Đura Jakšić, and the carved doors.

AR application. Since the iconostases, as unique architectural elements of the church interior can be seen only in situ, the main idea of the AR application is to allow a user with the possibility to visualize it outside the physical borders of the monumental interior.

Regardless the large dimensions of the iconostasis, in this way, the visualization of the entire structure of the iconostasis construction, as a big frame which, visually and physically, supports the icons, as well as the visualization of single icons, is allowed.

For this purpose, the previously optimized 3D model of the total iconostasis representation is used. AR application is developed using the Vuforia SDK that comes integrated with the Unity game engine. The whole application is made inside one scene in the Unity engine, while the changing between the AR scene and the main application page is performed only by switching between AR and the main camera, with the aim to achieve optimized processing time. This way, the whole iconostasis is visualized by detecting the printed marker throughout the camera of the tablet device (figure 5a).

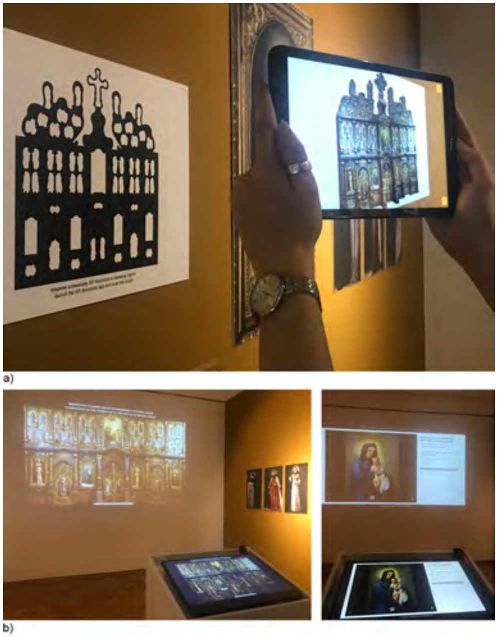

Figure 5 Multimedia presentation of the iconostasis at the museum painting exhibition of the Gallery of Matica srpska (Mišić 2019; [1]; [2]); a) AR visualization; b) Web application and the iconostasis orthophoto digital projection on a wall

Web application. Web application for the detailed iconostasis presentation is developed with the main idea to allow users to interact with the 3D model of the iconostasis in the virtual environment which provides additional options, such as more detailed visualization of the individual icons with accompanying information on the title of the work, the period of origin and the key characteristics that describe it as an art piece. In this case, the detailed representation of the first and the second iconostasis floors, with the obtained *GSD* of 0,90mm is presented as the digital projection of the orthophoto on the wall (figure 5b). The application provides options for click and zoom on one of the eight icons painted by Đura Jakšić, in order to visualize it in detail with additional text information on it.

MUSEUM MULTIMEDIA PRESENTATION OF THE ICONOSTASIS

This research presented an outcome of the collaboration between the university team and the Gallery of Matica Srpska in Novi Sad, realized throughout the museum multimedia presentation of the iconostasis. The painter Đura Jakšić and his artistic creation have brought together two national museum institutions - the Gallery of Matica Srpska and the National Museum in Belgrade - which have jointly realized the exhibition *Đura Jakšić. Between Myth and Reality* dedicated to the artist whose literary and visual artworks marked the Serbian art and culture of the 19th century.

Through three thematic wholes - portrait, religious and historical painting - the exhibition presents the visual art opus of Đura Jakšić. In addition to the paintings from the museum collections and from the Serbian Orthodox Church, his painting work in the Church of St. Procopius the Great Martyr is also available for viewing thanks to the implementation of modern technology (see figure 5).

CONCLUSION AND FUTURE WORK

This research presents the part of the wider study of the church heritage digitization and visualization, with the focus on the iconostasis. The paper explains the process of creating the multimedia presentation of the iconostasis, as the unique element of the Christians Orthodox church heritage. The multimedia presentation of the iconostasis is shown as part of the museum paintings exhibition. The iconostases are ornamentally shaped and decorated elements situated in the altar area of churches, on which religious paintings are represented. Since the visualization of the iconostasis is possible only in situ, the multimedia presentation provides the user with the possibility to visualize and interact with the church heritage outside the physical church interior.

According to the detailed analysis on the iconostasis structure and dimensions, as well as its characteristic position inside the church, we designed a methodological approach, based on specific church interior conditions, which depends on the desired level of detail of the representation. The proposed methodology for the 3D digitization and visualization an iconostasis has been tested on the particular case study and can be further applied to a number of other iconostases, with manipulation of only a few key parameters of the surveying process. Considering that the initial results are very encouraging, further testing and improving the methodology on other iconostases is of particular interest in future developing the proposed techniques for the church heritage digitization.

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A Digital Twin for Directing People Flow in Preserved Heritage Buildings

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This paper showcases a Digital Twin in the form of a simulation interacting with a BIM. As will be shown, such a combined can serve specific problems during building operation (here: directing people flow in preserved heritage buildings) .

Keywords: *People Flow, Heritage Buildings, Agent-Based Simulation, Building Information Model, Digital Twin*

INTRODUCTION

There are many buildings which fall under heritage preservation; among these are cultural institutions and museums which are frequented by a high amount of pedestrian traffic which must be directed for optimal access, security and safety reasons, and changing usage scenarios.

Solutions such as belt barriers offer a highly reconfigurable solution, however, they come at a high cost in terms of personnel. A further disadvantage lies in the fact that they do not blend in well, making the access area look like a security check rather than an integral part of the historical building.

This paper argues for retractable crowd control solutions designed to fit into the building's style. Instead of using personnel for reconfiguration of the access area, we entrust the building itself with the responsibility to manage people flow (see figure 1a) through use of an Agent-Based Simulation (ABS) acting on top of the Building Information Model (BIM), thereby forming a Digital Twin.

Our contribution lies in the following areas:

- We initially review the State of the Art in directing flows in heritage buildings (see "Background and problem definition") in order to establish a methodology for sentient buildings that are able to direct pedestrian flow (see "Methodology").
- We describe an ABS acting on top of a BIM, which computes the next state of actuators (e.g. barriers) using current and recorded pedestrian flow as well as preset rules (see "Digital Twin").
- We showcase the approach using the concrete example of the Palazzo della Civiltà Italiana in Rome (see "Case Study"), relating the results back to our Methodology and once again looking at the apparent discrepancy between heritage protection and implementation of solutions for management of people flow (see "Discussion").

As further contribution, this paper shows how a Digital Twin can be used in practical terms - an undertaking which has often been named in literature but hardly ever done to the extent brought forward herein.

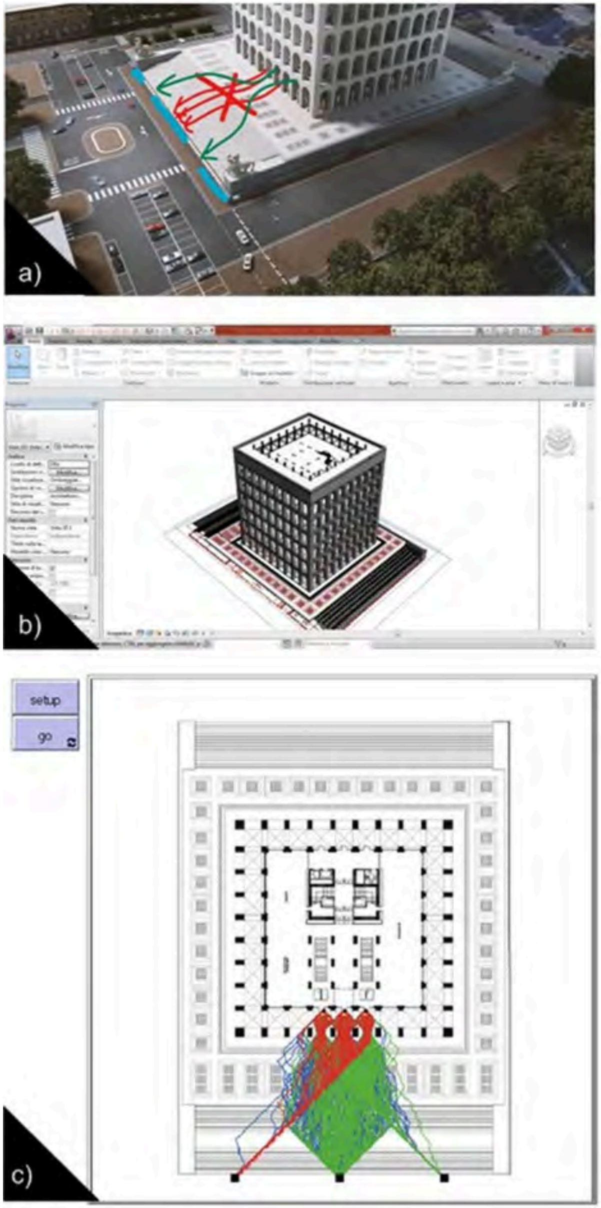


Figure 1
(a) Concept of Digital Twin for directing pedestrian flow to three exits at closing times (b) BIM representation of the building (c) Screenshot of ABS acting on top of BIM, actuating retractable barriers based on exit flow

BACKGROUND AND PROBLEM DEFINITION

A relatively high number of research work has been analyzed by the authors regarding methods and technologies for supporting design processes by enhancing the interaction between existing architectural components/spaces and their Digital Twin model.

Sharma and Tabak (2008) developed an ABS for design of spaces, both for static and dynamic cases. the model allows time-dependent analysis of flow incorporating dynamic route-choice models, agent behaviours and interaction, as well as stochastic variations. Al-Qattan (2016) developed an interactive and a responsive Tangible User-Interface (TUI) for parametric and Building Information Modeling (BIM) applications. The link between both environments associates physical objects with their digital design information to assist users in the digital design process. Haojie Hu et al. (2017) break down space into components and measure each with the straight sight-line of individuals, using Space Syntax Theory (SS-T) for simulations. They conclude that with the assistance of SS-T, Multi Agent Systems (MAS) can be more functional for solving sophisticated problems in real-life environments.

In the context of heritage buildings, implementation of BIM-based tools/methodologies is quite recent, and just few research results can effectively support designers in addressing users' behavior in the building. Intervention on old buildings, and even more the protected ones, has a dual, apparently opposite, goal: on one side the preservation of the existing values, starting from the testimonial evidence of the physic components; on the other side the renovation of functions, according to radically new activities to be hosted. Protection and restructuring/modification lay on the same direction, with opposite verses: a complex complementarity.

In fact, once recognized the artistic valour of the edifice itself and assumed the intrinsic value regarding the immutability of preserved elements, a consolidated philosophy for restoration requires the intervention to be: recognizable and reversible (Brandi 2005 [1963]).

Since the building lifecycle defines always changing requirements, the status of these solutions has to be reconfigured accordingly. Fences, belt barriers, advises, signals, lights constitute a kind of solution frequently implemented in practice, designed to be temporary and removable. Directing flows in a protected building, e.g. in the access area, is a key task for supporting different usage scenarios in efficient and safe conditions.

Simeone et al. (2016) have worked on behavioural simulation for heritage buildings use planning, integrating BIM with Game Engine. In their paper they claim that by distributing Artificial Intelligence among virtual users, process entities and building components they can provide the direct measurement of the impact on the artefact. However, this approach does not take into account the interface with the building, and vice versa, missing the requirement for a non-planned (spontaneous) use.

In the research framework presented in this paper, the authors goal is to grant the building itself with the responsibility to facilitate the management of the users flow in real time, also including local variations from the planned use.

METHODOLOGY

At the moment, the process of identifying and implementing a defined physical framework related to a specific usage scenario is relying only on:

- designer's implicit (function-action) knowledge;
- health and safety personnel, acting on the basis of the designers' predefined configuration.

This work aims at the definition of methodologies and tools for being able able to work on top of heritage BIMs in order to:

- make building usage knowledge explicit, based on data collection (here: of building user behaviour);
- implement a sensor-actuator system in or-

der to make the automation system support users' needs.

In that sense, this paper transitions from a purely manual scenario to one augmented/aided by a building automation system, enabling the building spaces/components to sense, reason and act (perform?) a required usage variation.

The general methodology for the technical implementation relies on the development of a system that uses sensors as input, an algorithm as intermediate black-box and messages to actuators as output:

- Sensors are used for recording people flow. Among the options in that context are (a.) explicit sources such as proximity sensors, access control crosses, or implicit sources, such as analyzed footage from visual or thermographic cameras, cash-desks, etc.
- The algorithm is generally a control system which has to reason over the sensory inputs for generating messages to actuators. In this case, we employ ABS as reasoning layer on top of a BIM.
- Actuators are used to influence the people flow physically. The modulation can use physical obstacles such as barriers, but also non-blocking elements such light tiles, signals/signs, dynamically projected content, etc.

DIGITAL TWIN

A Digital Twin is a model of a building which interfaces to the real building and vice versa. In our case, this is done by having the model of the building in a BIM (figure 1b) on top of which an ABS is used for algorithmic decision making (figure 1c). In more precise terms, our ABS initially loads a schema of the building which is a simplified floor plan. It then connects to input sensors on which it is ready to receive the current flow rate. In our case, these readings are artificially emulated by assuming a certain flow rate which changes through time. In practice, any occupancy sensor (direct - e.g. light barrier, turnstile; indirect - e.g. through an infrared camera whose image is processing via computer vision to get the amount of persons passing a specific [virtual] line) could be used.

After obtaining the current exit flow, the ABS then computes the amount of people which will fit through a retractable barrier comfortably in real time by (1.) predicting speed and arrival at the currently opened barriers which are assigned randomly to each simulated pedestrian, which in turn (2.) gives a density per barrier. If this density surpasses a threshold, then a next barrier is scheduled to open if possible. The decision can still be (3.) overturned by rules such as predefined schedules that define availability of barriers over the course of the day (example: max one barrier at the evenings, no barriers open during the night).

In cases where there are large fluctuations in the observed flow, one can also use historical data for that specific day and time to get an estimate; this usually happens in museums, where the time of payment acts as an estimator for inflow.

After reaching a decision, the ABS translates this to a message to be sent to the actuators (here: retractable barriers). To avoid constant fluctuations, it is usual to employ a hysteresis (implemented e.g. by introducing a voluntarily lag between triggering and executing the command sent to an actuator, which extends the lag or cancels the request if converse commands are received in the time window).

The opposite case, namely that a physical override (e.g. button which sets the state of a barrier) dictates the state of the Digital Twin, is also possible. For this to be possible, such manual switches must be interfaced to the ABS as well.

As side-note, a simulation model acting on the real world without validation is just an assumption; it would be useful to validate the computed assumptions by comparison with sensory data - here: The predicted exit flow with the actual exit flow - in order to establishing a feedback loop. However, since our case study was conducted purely in silico, it would not have made sense to reproduce our assumption (i.e. self-fulfilling prophecy). This aspect is thus left for the physical implementation which the author of this paper aim to do undertake in the near future.

CASE STUDY

Palazzo della Civiltà Italiana in Rome is a relevant historical building also known as "Squared Colosseum". This public property iconic building of particular historical interest, protected by Minister of Cultural Heritage, initiated with a design competition in 1935 for the planned 1942 world exhibition.

The Palazzo was designed by the architects G. Guerrini, E. B. La Padula and M. Romano and constructed between 1938 and 1943. It was inaugurated on November 1940 as the centrepiece of the Esposizione Universale di Roma neighbourhood (EU42). The structure is also considered one of the most representative examples, in the modern history of architecture, of rational synthesis of classical linguistic elements.

The Squared Colosseum consists of a box that stands on a wide base connected to the street level by two opposing staircases. The scale is imposing: the base covers an area of 8,400 square meters, and the building has volume 205,000 cubic meters with a height 68 meters (50 meters from the base; each level is 8 meters high).

The four faces of the prismatic solid, covered with slabs of travertine stone, are characterized by the strong rhythm of the arches in sequence (nine repeated openings for six floors), strong architectural motif that makes it instantly recognizable as one of the symbolic monuments of Rome.

Recently, FENDI, an international company known in the fashion sector, moved there its offices headquarter, renting the full building, including six floors used as open-space offices and a ground floor used as internal Cafè. The agreement with the Municipality reserves the first floor, on top of the stairs podium, to the public use, mainly for exhibitions free of charge.

Every day, because of its mixed use, the building hosts up to one thousand of persons, simultaneously: around 500 employees in the offices, plus 100 external consultant, and up to 400 visitors of the exhibition.

The problem with controlling the people flow from and to that building is becoming a relevant one. Specifically, the internal flows are comfortably defined by the ample spaces, large stairs and optimised management system for the four lift, but the access from the street to the external monumental stairs and from these to the internal reception area, can be critic under certain conditions.

For instance, it can happen that - non necessarily in case of an extraordinary risky event - a relevant charge of Palazzo inhabitants should get out at the same time, while the external barriers, standing in front of the first ground level step, are closed according to local regulation.

In order to satisfy requirement for both, health and safety and security control, the flow must pass by the main three doors, glide by the external stairs and converge toward the adequate passages on the external barrier.

Controlling that everybody is out, and nobody gets in without permission, in the context of this wide space, when the night comes and when a crowd of pedestrian are moving around is a task that must be solved by enabling the building itself to automatically optimise - in real time - the appropriate number of passages.

As for technical solutions, there is currently a BIM model which was produced in course of a project (Trento et al. 2014), however this is not being used to its full extent in practice; in this paper, we have therefore chosen to base our solution to the problems mentioned before using that BIM model as a basis, so as to point out its potential also in building automation and control. The conducted case study is thus aimed at both at a scientific audience as well as building owners/operators (i.e. the E.U.R. district administration which is part of the city of Rome).

Since getting permission for setting up sensors and actuators is a lengthy process even for a test case - not only because of heritage preservation but e.g. also due to privacy reasons connected to the EU General Data Protection Regulation (GDPR) - we opted to emulate these parts in silico as part of the ABS.

Out of the existing BIM model we exported a floor plan of the ground as bitmap, rasterized to 0,5m/pixel. Considering that the shoulder length of a pedestrian is roughly in that range makes this approach feasible for use in a people flow simulation. The floor plan (see again figure 1c) is roughly divided into (1.) the access area, where we have three retractable barriers, (2.) the three entrances to the building and (3.) the inner area of the building itself.

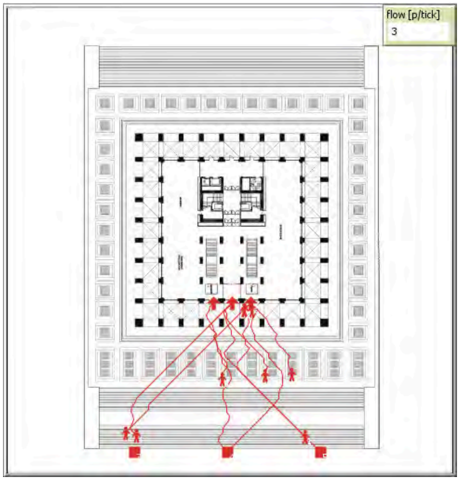


Figure 2
Simulation

The principal operation of the simulation is to generate agents at a certain (customizable) rate in the building entrances who want to get to the open barriers (figure 2). This rate is read either dynamically from an external source (i.e. real-time input or recorded input) or manually within the simulation. To direct agents we used static routing along the shortest path without computation of congestions and blockages due to physical contact among and between pedestrians and their environment. This approach is reasonable for cases not involving emergencies, however, for such high-density situations proper pedestrian dynamics algorithms (e.g. Helbing et al. 2000) would be needed.

The "sensors" and "actuators" are modeled as own type of agent in our simulation:

- Sensors measure the average rate in a configurable time window (here: 10 "ticks" of the simulation) and along a virtual line that spans all three entrances acting as "start";
- Actuators are agents modeling retractable barriers; they can be in either "open" or "closed" state and can receive requests for setting their state.

The core of the simulation then lies in predicting the density in a configurable time window by examining the computed paths for all agents and estimating their time of arrival. If a configurable density within the time window is surpassed, then a request for opening another barrier is issued. The request is processed by a second stage which assumes it is either day (therefore letting the request pass since the building is principally open), closing or night time (denying the request). A physical override is modelled by three tristate switches (true/false or not set) in the simulation, which gives the final processing stage that always wins. Once a decision has been made it is sent to all actuators that need to be changed. The request is carried out immediately (no hysteresis). As a result, we can see roughly three "epochs" of pedestrian flow (refer again to figure 1c): One where there is only one barrier open, one with two and lastly one with three.

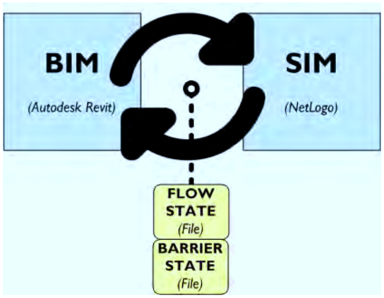
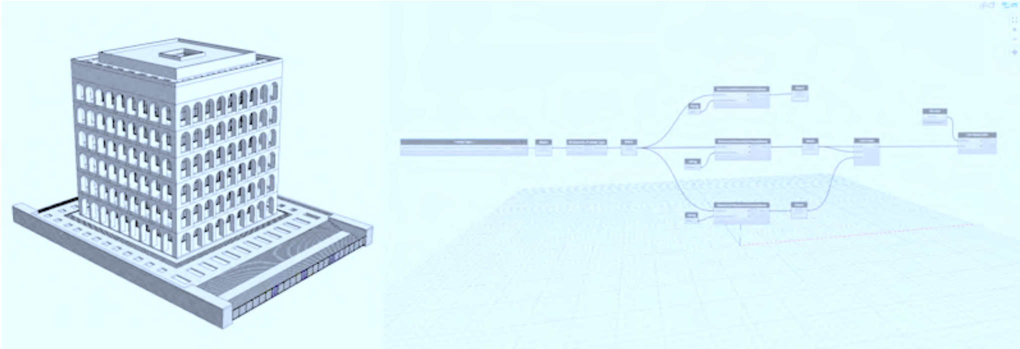


Figure 3
System Diagram

Figure 4
The export of state from the BIM happens through a custom algorithm in Dynamo



DISCUSSION

Seeing a Digital Twin as a black-box between sensors for input and actuators for output, as this work has done, is not always the meaning in which authors refer to it. The main intention is a replication of a real system and a representation (i.e. model), sometimes with (uni- or bi-directional) interfaces between the two. Technically, this is accomplished by two shared files (one for the flow, one for the barrier state, see figure 3) to which both BIM and simulation can write. The BIM side is handled by Dynamo in Revit (figure 4), the simulation side by NetLogo (figures 1c and 2). The files can also be updated from an external source ("sensors") and thus allows for real-time interfacing, which is currently being emulated in NetLogo for testing purposes.

Especially in heritage, the choice of sensors and actuators is limited: Issues of heritage protection, reversibility of interventions, privacy protection, ruggedness for use in outdoor environments or simply staffing problems come into play. On the other hand, the Digital Twin proposed herein offers a possibility for managing people flow for sake of safety and security, different space utilization scenarios and proper night-time closing procedures. This now stands in contradiction to the all points mentioned before. However, both points should not be viewed as contradictory, there needs to be a synthesis which can only happen between building professionals running the Digital Twin and the building owner/operator, regulation-makers and, last but not least, the wider public using the building. A closed-loop (fully autonomous) system will certainly be problematic in that case, which is why we have included a manual override into our considerations. Another approach would be to take the Digital Twin only as expert system and let the building operator be the sole responsible for decision-making; this approach also seems the safest from a legal standpoint.

CONCLUSIONS

This paper has put forward a practical example of a Digital Twin controlling the people flow from and to a preserved heritage building. This was realized by means of an Agent-Based Simulation on top of a Building Information Model, which receives data from physical sensors installed around the building (people inflow) and changes the state of physical actuators (retractable barriers controlling outflow). The reverse way - namely interfacing physical controls (buttons, switches) to this virtual representation is also possible.

After analyzing the State of the Art, the authors conclude that the few Agent Based Simulation currently implemented in heritage buildings do not take into account this physical interface with the building. A second aspect which is yet to be covered is the introduction of a non-planned use, e.g. via physical override or insertion of new rules for the computation of state actuation at runtime; in the latter we see a field for future research still to come.

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A New Approach to the Cultural Heritage Documentation Process

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Looking at the existing tools for preservation in patrimony, we perceive an over-appreciation in material heritage conservation over intangibles. Through the implementation of algorithmic documentation methodology, to obtain information that composes a certain cultural expression, this paper aims to present an attempt to expand the tools of documentation and registration of cultural heritage and also the applications of this approach for a language implementation with a propositional aspect.

Keywords: *Cultural Heritage, Parametric Modeling, Process Documentation, Shape Grammar, Brazilian Design*

INTRODUCTION

Looking at the existing tools for preservation in patrimony, we perceive an over-appreciation in material heritage conservation over intangibles. According to Fonseca (2003), for more than 70 years the expression "historical and artistic heritage" evoked among people the image of a set of ancient monuments that we must preserve, either because they constitute exceptional works of art or because they have been the scenery of remarkable events , referred to historians' documents and narratives.

Heritage, by the 1988 Federal Constitution of Brazil (2016), is defined as "material and immaterial nature [...] bearers of reference to identity, to action to the memory of the different formative groups of Brazilian society." Therefore, collective cultural expressions also represent the nation's imaginary and deserve instruments of conservation.

According to Fonseca (2003: 69p), heritage is not only buildings and objects deposited in museums, written and audiovisual documents, kept in libraries and archives. Interpretations and institutions, as well as legends, myths, rites, knowledge, and techniques, can be considered as examples of intangible heritage. In many cases, the patrimony physical protection is unfeasible, even though this is not the most appropriate logic of preservation. What matters is to ensure the reproduction process continuity, preserving and guarding the ways of doing and respect for values such as the dynamics of doing and the adequacy of useful technique, for example.

The distance from practices and contexts sometimes does not take into account that all material patrimony is a reflection of intangible cultures, which use matter as way to support expression. Therefore, isolated objects are not enough to preserve cultural praxis, because they represent a sample of a shared repertory of experiences that manifests itself as living language changing in time, carrying characteristics of each people identities.

The focus on intangible heritage seeks to preserve expressions which are presented in material instances but have their power in their processes, actions, and ways of doing. Fonseca (2003) affirms that the most authentic values of identity are discovered from goods coming mainly from the popular making, which are not considered cultural goods because they are inserted in the living dynamics of daily life. So, if the heritage has material bundling, its language formalization can bring new understandings about its cultural identity.

HYPOTHESIS

Would be possible to expand forms of documentation and recording of material patrimony so it could capture nuances of its immaterial counterpart and cultural changes in time? Could heritage documentation expand design practices? Also, could parametric modeling tools help in this expansion? According to Fonseca (2003) this process is not only possible but necessary:

Some considerations must be made to help map out this new and broader Brazilian cultural heritage representation, and to draw up methods that contribute to the approximation of the cultural heritage produced in the country, especially in the issue of intangible heritage. The process of re-reading the question about cultural heritage is not exhausted at the conceptual level. Instead, it requires the involvement of new agents and the search for new instruments for preservation and promotion.

Faced with this is the consolidation of computational tools, in which it is possible to capture not only the object but also the logic that constitutes it. Through an algorithmic description of the objects it is possible to characterize them as a sequence of operations of the raw materials, and thus to approach the documentation of the process. Thus, the application of parametric tools for memory preservation seeks to register the forming process, since this looks an all-embracing approach in comparison to the simple documentation, sometimes sacralized, of individual objects.

This immaterial process layer is present in the logical description of the steps in algorithm coding since the sequential aspect of this type of approach requires that all the forms and the processes be clearly described by geometric and mathematical tools. Therefore, according to the documentary objectives of the present research, non-parametric modeling proved to be insufficient, since its approaches considered the object as a model and not as a set of rules and processes, a limitation that is no longer found in parametric modeling. That is when describing in just one algorithm the logical chain is possible to reach the various models, pointing out that such an approach is appropriate for documentation of local cultures because it represents a large amount of information, extrapolating the possibilities of cataloging models.

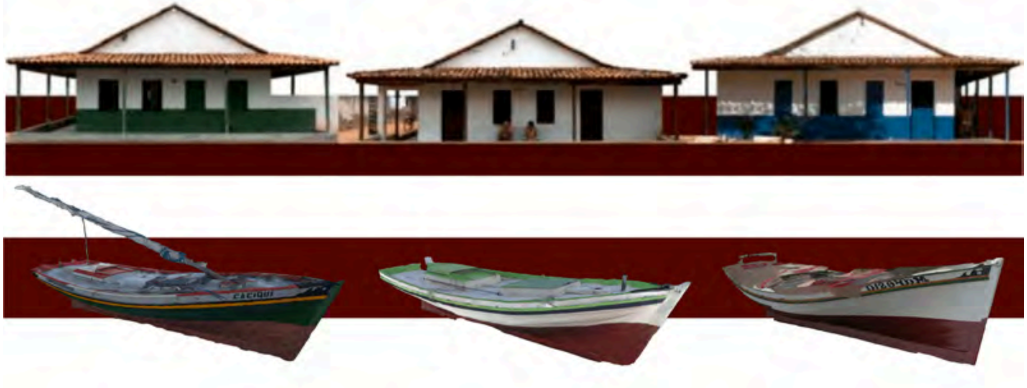
OBJECTIVES

This paper aims to present an attempt to expand the tools of documentation and registration of cultural heritage. As a case study, the parametric modeling tool was applied as a means of documenting two typical Brazilian cultural expressions, located in the coastal municipality of Icapuí in the state of Ceará, Brazil: the houses of fishermen and their boats, both built by local hands of naval carpenters and builders, see figure 1.

METHOD

Being an inferential method (Cardoso 2010), the first moment, in the field, is the survey of a large number of houses and boats, searching for their recurrences and identifying the main elements of their grammars, as well as an interview with the masters who mastered these ways of doing. Manual and photogrammetric surveys were used for the research. (Photogrammetry Figure) With these results in hand, it was possible to apply inductive analysis that clarified the patterns and stages of production of the two objects. To formalize the language in dia-

Figure 1
Typical houses and boats of Icapuí city



gram representation, the process was described, exposing the technical limitations, formal preferences, ways of thinking, technological advances in manufacturing and nuances of their ways of life. The process was coded for algorithmic representations on two parametric platforms: Python for houses and Rhino+Grasshopper for boats.

RESULTS

Throughout the implementation of algorithmic documentation methodology, to obtain information that composes a certain cultural expression, it is necessary to compare similar individuals, instantiated materially as a representation of the abstraction that is their language. The symbolic dimension of a cultural expression needs a material substrate so that through it it is possible to make abstraction into intelligible phenomena. Therefore, in order to access parts of the ontology either from boats or houses, it was necessary to notice in the samples which elements remained between objects, and the composition of such recurrences pointed to the formalization of the two languages.

Shape grammar was chosen as formalization method, since analytic grammar benefits from the extensive collection of data from individuals, as evidenced by Celani (2006): "analytic grammar consists, first of all, in choosing a set of works [...] which, at first sight, bear some resemblance to one another. "

Once the processes that result in the objects have been clarified and the information described by the masters in the interviews has been explained, algorithms have been implemented capable of sequentially constructing the objects, besides their codifications have variations that produce coherent cutouts with the studied ontologies. Processes were documented, not just process results from individuals.

The logic synthesized in the study of houses was implemented in Python and brings with it the different stages of zoning composition of the spaces, as well as the geometric constraints imposed by the proportions found in the sample field of analysis. Initially, the shape and proportions of the plant are retracted forming the porch and the living zone, which in turn was decomposed in the other spaces of the program. The relationship between the environments is governed by the topology also extracted from the samples, and the organization of such information in the form of graphs allows to implement not only formal but also programmatic aspects, see figure 2.

The boats were implemented in Rhino + Grasshopper, demonstrating the step-by-step con-

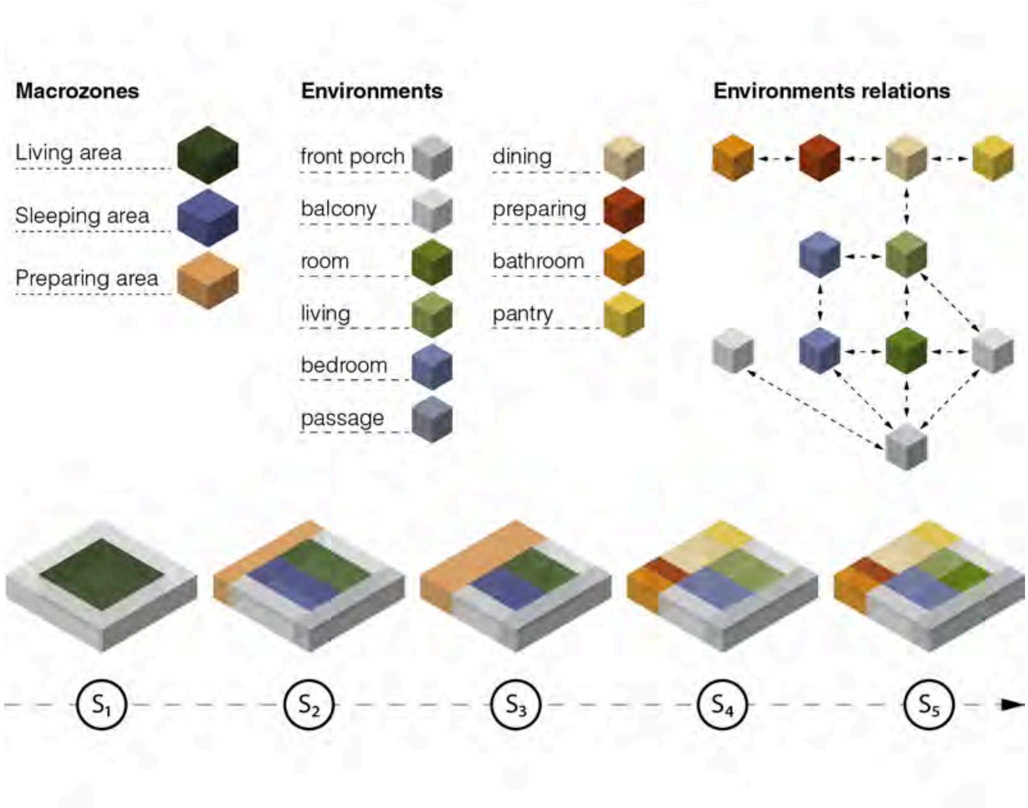


Figure 2
Diagram of the house

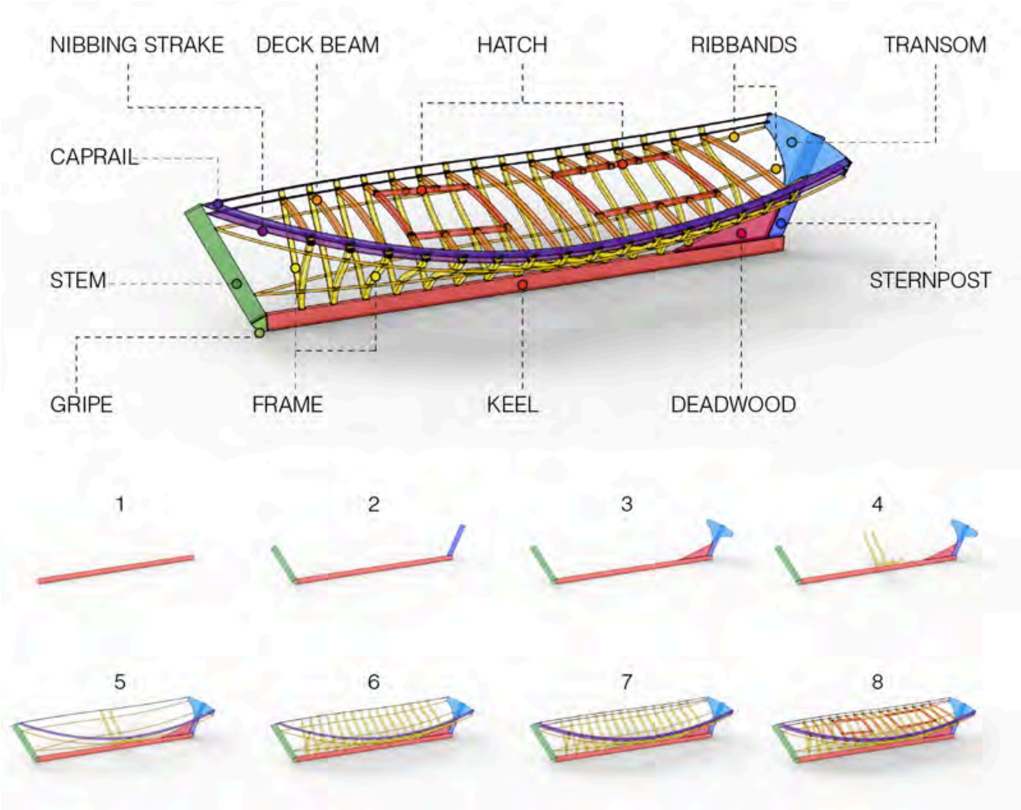
struction of a boat, allowing the variations described by the masters. The layout of the keel and master caves, see figure 3, proved to be the most important since they determine the proportions of the boats. In addition, the colors of the hull, the shape and position of the sail and the shape and position of the talhamar and cadaste help to characterize and differentiate the boats of Icapuí from other families of boats. The more trained look of the masters carpenters and residents of the region of Icapuí, can identify, through different characteristics, who built each object, whether house or boat.

The models of the boats and the houses, generated by the algorithms, were printed in 3D and presented to these masters carpenters and residents for validation of the objects while form and process and possible identification of the constructor of the model. See figure 4.

DISCUSSION

The parametric documentary approach contributes to cultural heritage since the algorithmic description is capable of carrying with it more information pertaining to the ontology of a clipping of individuals than its morphology and materiality. The need to sequentially describe the process, store information

Figure 3
Diagram of the boat



regarding the techniques and actions employed, as well as the relationships between the parts of the object. Thus, the present work proposes an approach of the formalization of languages, that structured in a computational tool, approaches the cultural complexity of the historical cuts. In this sense, digital processes and computational thinking often act as an accelerating tool for the creation and optimization of projects aimed at preserving and preserving a memory, since many of the processes used (photographs, videos, written documents) are sometimes ineffective at documenting the procedural nature of artifacts.

According to Fonseca (2007), today, we face the expansion of the notion of cultural heritage, and, consequently, the challenge of preserving processes. We know that it is not possible to preserve them without the participation of producers and all the people involved in their production, consumption and transmission dynamics. We also know that it is not possible to preserve them by simply using the power of laws and the refinement of techniques, and we also know that the preservation of their physical support is not sufficient for their safeguarding or for the full transmission of their memory.

This approach, as it was done in view of the sequence of design and constructive choices of objects, is a way of expanding heritage documentation, complementing other forms of registration, and evidencing the design choices of masters. This evidence is also useful when noted the possibility of making the choices and reimagining them in new projects, bringing the choices of the past closer to the act of designing today. As well as the biological concept of memory described by Aloísio Magalhães (1985):

When one speaks of memory in a figurative sense, when one lends the idea of memory to any one fact, there is usually a tendency to become something like" putting together "or" holding "something," holding back. " And this seems to me unsatisfactory, I prefer the biological concept of memory: to guard, to retain, and then to mobilize and to return.

Nowadays, the new masters do not build only sailing boats, but motorboats. They use the same language but now adapted to the new technologies available. This caused the proportions of the boats to change, leaving them wider and steadier, but slower, since the job of moving the boat is the engine, see

Figure 4
Residents and builders with the 3D printed model

Figure 5
Two models of boats generated

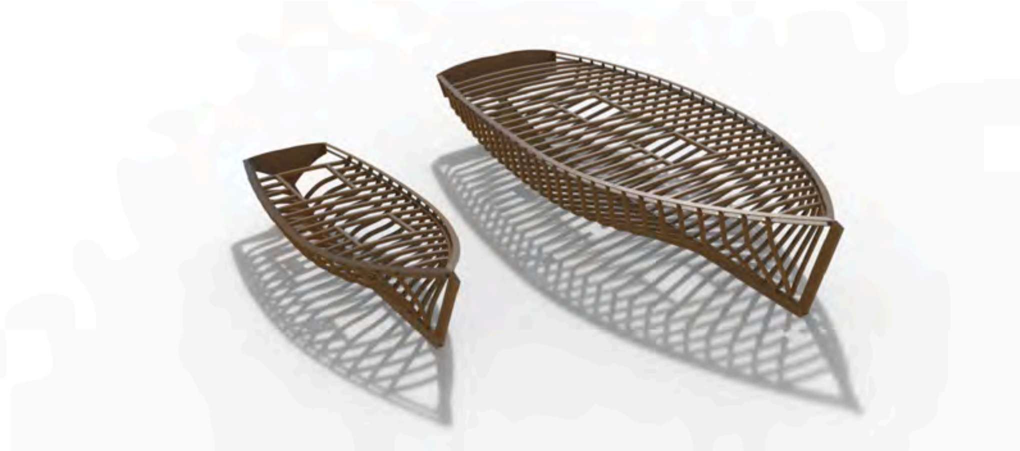


Figure 6
Beach house by Daniel Cardoso

figure 5.

Another development of the language one of the applications developed by Daniel Cardoso was the adaptation of the traditional language of the houses of the fishermen in a new program. Its beach house uses the same proportions and language of cover, however creating a free modern plan where the spaces are arranged without partitions. See figure 6.

According to Magalhães apud Anastassakis (2012) A culture is evaluated in time and is inserted in the historical process not only by the diversity of the elements that constitute it, or by the number of representations that emerge from it, but especially by its continuity. This continuity involves changes and changes in an open and flexible process, of constant feedback, which guarantees a culture its survival.

In addition, as a result of this line of research, new applications of this approach to language implementation are being developed at the Federal University of Ceará, now with a propositional aspect. The architectural programs of the popular house, the popular market, and new models of boats are being developed.

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Design - ALGORITHMIC AND PARAMETRIC 1

Interventions in the urban setting through generative design and digital fabrication

Three study cases in the city of Montevideo

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In the last few years, much has been written regarding morphological generation through computer-assisted means, algorithm design and digital fabrication. Nonetheless, the purpose of this article is to build, from a social perspective, three different narratives based on three specific study cases in the city of Montevideo. Based upon them, the aim is to reflect on the development of projects at a 1:1 scale in the local university context and its connection with society.

Keywords: *digital fabrication, urban intervention, generative design,*

INTRODUCTION

These three study cases that have been selected refer to the work carried out by the University of the Republic through the FabLab.MVD laboratory, with the collaboration of different colleagues and teachers invited from other universities. Thus, efforts were made to produce a mix based on different conceptions and different visions and ways of approaching reality.In terms of its urban layout and architectural production, the city of Montevideo has a brief history. Founded between 1724 and 1730, it urbanistically refers to a Spanish colonial layout which was subsequently expanded and intervened on, but architecturally nurtured with renovating architecture, where the experimentation of art déco and brick architecture from the 1920s onwards, interspersed with historicist architectures have built an eclectic ix of styles that has been brewing the image of the city.This project refers to three interventions in different points of the city, involving specific actions of production of the city in terms of projective prosthesis.The projects hereby exposed were carried out with the collaboration of undergraduate students through workshops and seminars on the application of digital fabrication techniques in the urban setting and its impact in the social appreciation of it.

Figure 1
Map of the city.

METHODOLOGY

Among the learning tasks of the undergraduate students of the School of Architecture, Design and Urbanism of the University of the Republic, workshops and seminars were conducted to foster reflection and the creation of interventions in the urban setting, especially in socially recognized buildings both for their architectural value and for their importance in the historical development of the city.

The premise of the three study cases was the use of parametric design tools (Rhinoceros + Grasshopper), the creation of algorithms connecting the shape of the pre-existent building to the target shape, and its production through digital fabrication techniques. The three cases were studied and designed in the classroom, produced in the laboratory, and subsequently assembled on site.

Case 1. The urban symbiont

The Ciudad Vieja of Montevideo is the name of the old center of the original layout of the city. There, the most emblematic buildings of the neoclassic period are located, among which the Misiones building, work of German architect Karl Tramabuer, stands out.

This building, considered architectural heritage of the city, suffered a collapse in the dome located in the northeast corner, caused by the passage of time and the poor state of preservation. The void generated by the lack of a dome was the excuse for the construction of a new message, adding a tectonic prosthesis to the original project. This prosthesis, in symbiosis with the building of Trambauer, intends to reestablish the original shape through the introduction of a new body. This is, not a parasitical structure but a symbiotic one with the original project, which aims to recover the dialogue between the city, its inhabitants and the intervened building.

The symbiont, as it has been conceived, is an object created from an ideal shape (the original dome), which has undergone different experimental plastic actions. The result is a strange but symbiotic object with parametric genes, created through digital fabrication and handmade assembly.

Figure 2
New dome installation.

It was developed with Rhinoceros y Grasshopper tools. The process consisted of three phases: first, the development of the theoretical concept and the discussion of the different methodological aspects. This phase focused on the conceptual development of the digital paradigm associated with the problems of the parasitical relationships in order to create ideas between complex generative processes and the parasitical behavior in the pre-existing systems.

Secondly, the testing and selection of the generative system. How to create a shape while setting aside the function and aesthetic variables? The first tests included models of traditional domes which were affected based on a sequence of cross sections. In the repetitive process of shape production, variations were introduced, small alterations in the generative patters in order to slightly interrupt the lineal decrease of the gravitational forces through the cover of the dome. These initial tests turned into a dome shape whose generatrixes move, turn and go backwards according to the variations in the generative pattern. The traditional dome is distorted but the shape is still preserved.

The same formal logic which builds the traditional dome is used to rebuild this new object. The third and last phase was the manufacturing and installation of the device in its place. Finally, the object was placed following the logic of its formal generation. The generatrixes affected for the dome-parasite are the ones that were mechanized and assembled in order to rebuild the shape. The urban impact of an ephemeral, low-cost object in a recognized building was significant, developing social reactions of different types.

Given the peculiarity of the intervention, an urban attractor was created. Initially, the neighbors showed mixed emotions: from complete acceptance to strong rejection, and all shades in between. However, at the moment of removal, after the stipulated time of permanence, the owner of the building decided to keep it. Furthermore, the inhabitants of the area embraced it as a part of the view, and the market value of the building where it was located had a major increase, despite its low maintenance at the time. Far from this last issue, which departs from the tasks of the exercise, it is of paramount importance to emphasize the significance that a simple gesture of intervention with a strange object in a pre-existing building can have. Perhaps the way of turning a parasitic object into an urban symbiont. This work was conducted with the direct and committed collaboration of architects Federico Lagomarsino, Rodrigo Martín Iglesias, Alejandro Schieda and Santiago Miret.

Case 2. Gran Salvo

Another example of urban intervention that involved digital manufacturing and social interaction. The Palacio Salvo is probably the most typical postcard of the city of Montevideo. Once again, a dismantled shape was the perfect excuse to integrate a designed and digitally produced object in the structure of the building. The place of the collapsed lighthouse was occupied by Gran Salvo, a metallic structure designed in order to replace the original lantern of the dome. Gran Salvo is a large object that combines light and form. The lights are controlled by a Raspberri Pi and people can interact with them, defining the colors, intensity and brightness of the light during the night.

It was also designed to face strong winds and, in the same sense, its morphology follows aerodynamics lines. The old building and the new structure complement each other in a way that creates a new urban shape in the city. In keeping with the new developments of the IoT, where ordinary objects are connected to the Internet, the intervention also adopts this tendency in an urban scale. The participation of the light as a central element of the project was majorly defined with the support of programmers and engineers and was implemented through a system led by RGB and its respective controllers.

Figure 3
Palacio Salvo after the installation of the structure. Ph. Drone5.

Figure 4
Gran Salvo. Designed by Federico Lagomarsino

Its handling is versatile and adaptable to different uses, color changes, intensity and production of content, creating a potential hardware to be programmed in different ways and with different functions.

The intervention in the Palacio Salvo generated a wide range of perceptions, from the most absolute rejection to the highest praise. In any case, the minority reaction was indifference.

The object was inaugurated with media coverage in all central news. The team who was in charge of the execution, led by the architect Federico Lagomarsino, had to carry out interviews in the media which cooperated to the social debate regarding the meaning of heritage and the willingness to intervene it or leave it just the way it is. Montevideo is a city with little history, but, even so, these kinds of debates enriched the academic scene. Thus, the ethical discussion about the dilemma regarding historical reconstruction or the new intervention arose. Distances and scale aside, this is a controversy similar to the current debate about Notre Dame in Paris. Even without having the controversy being settled, Gran Salvo, created to be an ephemeral intervention, still continues to be positioned in place of the dome of the Palacio Salvo. There it remains, illuminating the city and bonding with its "younger brother", the Palacio Barolo on the other side of the Río de la Plata, just as its creator Mario Palanti wanted it.

Case 3. Dieste Pavilion

Probably the most ephemeral construction of all the three chosen cases, it was conceived as a sort of homage to the well-known engineer Eladio Diesto by following the spirit of his style and shapes. The design was in charge of the recognized Spanish architect Andrés Martín-Pastor who was a guest teacher from our laboratory for the workshop which brought the Dieste Pavilion to life.

Therefore, the result is an MDF pavilion designed by three developable surfaces that compose a curved shape that evokes the walls and ceilings of Dieste, as in the Church of Cristo Obrero, for example.

Apart from becoming a global trend in several cutting-edge university centers, the execution of pavilions is an opportunity for the construction in 1:1 scale of complex morphologies, capable of conducting different mathematical notions of descriptive geometry. With this practice, the goal is to convey basic geometry concepts to the students, applying these to the design and to a constructive exercise.

The case study is a light structure, made completely out of wood (MDF). It was proposed as an ephemeral, light, low-cost architecture, capable of being reusable and assembled with general guidelines or even an instructions manual. This architecture is based on the geometric properties of the developable surfaces. The limitation regarding the need to invoke surfaces of revolution results from the choice of manufacturing method, based on the cutting of 4 mm thick sheets of plywood. The prototypes proposed are self-supporting skins made of a single layer of material.Because of the use of parameterization algorithms, it has been possible to implement these complex surfaces in flat pieces that were cut using CAD-CAM technology. These were assembled on the floor like a big puzzle and were then curved cold in the final destination site in order to get their final form and rigidity. This curvature was achieved by its own geometric shape. The proposed system tried to give an architectural response based on the logic of limited material resources (a thin sheet of material) and minimum assembly cost (self-construction), while generating a real production experience in atoms of a digital construction in bits.

Unlike the previous cases, the construction of the Dieste Pavillion was not a prosthetic intervention on a pre-existing building, but an ephemeral construction in itself. As a general concept, regardless of being a shape evocative of Dieste's style, the project served as a 1: 1 scale construction experience in a geometrically complex way and as an example of planning and collaborative execution.

DEBATE

Following this brief summary, some topics emerge, which intend to be the core subject in this paper. In the Latin-American university context, there still exists a collective imagery in which the digital teaching

Figure 5
Dieste Pavilion in place.

Figure 6
Dieste Pavilion. Design by Andrés Martín-Pastor

refers exclusively to the use of representation tools, where there is no room for the projective area. This Albertian ideal focuses on the acts of creation and execution of the project as two different moments, where the latter is a consequence of the former, and both of them are not a unique act of creation.

In the cases presented here, beyond the results obtained, the intention was to generate a reflection on the digital as a design tool, in all its stages. In the context of the fourth industrial revolution, the redefinition of roles in the act of creation forces us to rethink creative structures. Not only from the actors involved in the creation but also from the users of the same.

Mass production is replaced by mass customization, and in that act a change of paradigm occurs where the notion of authorship is diluted and merged in the collaboration of all intervening parties. The understanding of this idea is essential in order to face the act of projecting and executing, seen as a single act of project.

Moreover, the idea of transposing atoms and bits, which is called "physical-digital convergence", also supports the conception of uniqueness between thinking and doing, as a collective and collaborative reality, where physical reality is only a transposition into atoms of the digitally designed reality.

Finally, and as a final thought, it is important to highlight the social implications of field work in the training of architects. The execution of interventions at a 1:1 scale as an example of how to project must have a parallel as an experimental field, where the urban insertion also has a strong bond with society, generating and building bridges capable of forging at least one part of the identity of the city. In the context of the Latin American city, in particular the city of Montevideo, the intervention in strategic points with actions from the academy serves to forge bonds and bring the work of the university closer to the city's everyday life. This is perhaps the main challenge that must be faced right now.

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Convolutas

Developable strips and digital fabricated lightweight architecture

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The present research is mainly focused on the development of a system that would be able to offer the potentiality of constructing free-form surfaces by using developable surfaces. Through a deep revision of pre-computational traditional geometric systems based on the classical Descriptive Geometry, after a re-interpretation that design and algorithmic generation tools allow by using computers and digital fabrication hardware as testing ground, a geometric control process has been designed in order to offer the possibility of managing double-curvature complex forms and their adaptation by using developable surfaces. The focal point of this system is proving how developable surfaces are suitable to build architectonical elements at real scale.

Keywords: *Geometry, Developable Surfaces, Algorithmic Approach, Digital Fabrication*

INTRODUCTION

This research is mainly focused on the development of a complete design system where geometric control, scale prototypes fabrication and big scale physical fabrication would be embedded and interrelated, being tested as experimental pavilions. In this way, the whole process has been closed starting from the basic computer aided design to the fabrication of final functional elements by means of digital fabrication tools, which allows a complete control throughout the whole process.

The construction of free-form surfaces is restricted to what is possible by means of graphical and constructive control. Regarding this subject, the adaptation of free forms through the use of developable surfaces by using different geometric systems has been an important line of research in recent years. Although nowadays there have been different important approaches (Shelden et al. 2002, Glymph et. al. 2004, Spuybroek 2004, Pottman et al. 2007, Piker) we have followed some issues that come directly from the Classical Descriptive Geometry Theory (Monge 1850) jumping from physical to digital drawing systems that nowadays the use of certain CAD software allows. The approach came from the enhanced graphic thinking via-Geometry based on Graphics-(Martín-Pastor 2019) pass through the common digital software and hardware tools and reach physical developments where the systematization of these theoretical developments actually prove their constructive validity.

The main objective of this research consist of finding results that can be extrapolated from the theoretic geometrical realm into the physical and

Figure 1
Graphic development of Torqued Ellipse by Richard Serra. (Image and Drawing by the authors)

constructive environment, maintaining the design and fabrication processes under exhaustive geometric control through all over the process. For that purpose, several types of prototypes and small pavilions have been fabricated using cardboard and small thickness plywood panels. This material is quite suitable and fast to be machined by means of a milling or laser-cutting machine tool at almost any digital fabrication laboratory all over the world.

GEOMETRIC BASIS AND METHODOLOGY STATEMENT

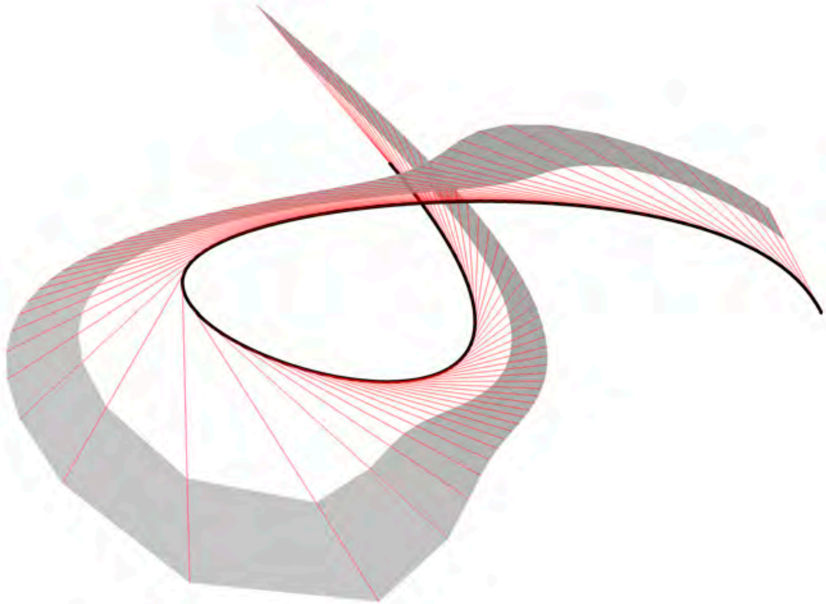
Overall, the movement of a plane through the space generates a developable surface. In order to obtain this kind of surfaces we have to introduce some constraints to this movement. Specifically, one of the ways we can obtain a developable surface is by sliding a plane tangentially leaning along any pair of curves. Whether they could be planar or warped curves, this plane is tangent to these two curves at least at one point along each one. The line that joins this pair of points will be considered as a generatrix of the developable surface that the moving plane generates. Some authors have referred to these kinds of developable surfaces or developable strips with the specific name of convolutas (Asensi, 1999). In some treatises about Classical Geometry these processes have been developed manually by using auxiliar graphical systems (Taibo, 1983), the graphical manual layout of these kind of surfaces is not in the habit of raising difficulty when at least one of the curves is planar. The process turns out much more complex when both curves are warped and in the case of free curves, the system appears unapproachable without the support of CAD software.

This type of planar or developable elements is used because of the simplification and economy that it offers regarding to economic and constructive aspects. A developable surface can be constructed from a planar surface, and the other way round a developable surface can be deployed on a plane without any crease or distortion. This question is decisive in manufacturing complex surfaces within any kind of constructive system, whether it would be a front facade panel or the hull of a ship. From the geometric point of view, many aspects define a developable surface. One of the most determining is its Gaussian curvature, which at any point over a developable surface is characterized by having always zero value.

Because of that and despite of the complexity concerned to this special kind of surfaces the practical use of them is widespread among not only engineering, architecture and naval construction but there are also some remarkable sculptural works (figure 1) that are based on this geometric system. (Koman, Serra)

In order to systematize the design process, some different approaches and algorithms has been generated, refined and customized following and rewriting

Figure 2
Developable
tangent surface.
Concept.



the common theoretical mechanism referred above by using parametric tools, specifically Grasshopper plugin for Rhinoceros. These approaches allow the application of the system by using any pair of spatial curves that would be defined; these should always be constrained among some specific intrinsic geometric parameters that reduce somehow its scope. (Quintial et al. 2012) The refinement of these processes have resulted in the theoretical concept and the geometric definition that is described below and it was used to generate the constructive elements that are hereinafter described in this paper.

The developable tangent surface (figure 2) is generated by transition of the different tangent lines, which are traced to a curve. From the pure geometrical point of view is the only developable surface that can be obtained by using a line or vector directly associated to a curve in different way that the general system previously proposes by meaning the movement of a plane through the space.

Given two warped curves it can be easily traced their corresponding tangent developable surfaces. These two surfaces could have an intersection along another warped spatial curve - it would be possible only if they do not belong to parallel planes, in this particular case they would have an improper intersection at the infinite -. From each point the intersection curve will be divided, in this way several pairs of straight lines can be traced from these points that would be tangents to the original warped curves, namely taking any point along the intersection curve would be a pair of straight lines that cutting at this point will be tangents to both original curves. The latter two tangent straight lines actually are secant one to each other therefore they determine, as could not be otherwise, a tangent plane to both curves.

The segment of line that is obtained by the tangent point at the curves constitutes a generatrix of the developable surface. Moreover, the developable strip that rests on both curves is achieved by the tran-

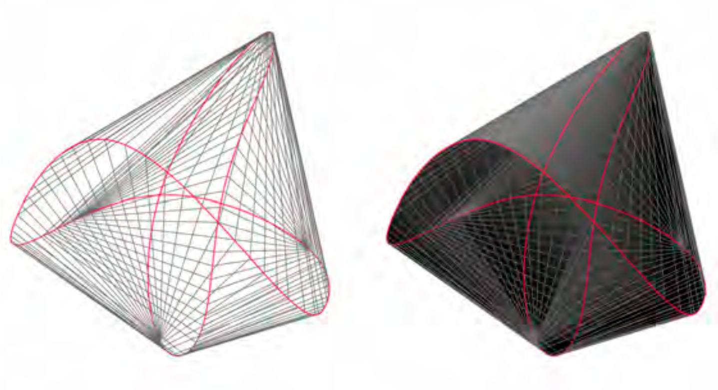


Figure 3
Convoluta obtained from two warp closed curves

sition of several segments. (figure 3) Hereinafter we will name this developable strip as convoluta in the way is named in the previous referred literacy.

The graphic statement described above is affordable by using computational graphic tools, as in our particular case the plugin Grasshopper. The process turns out quite simple to be arranged into a logic definition just by following the steps that are described. The most important theoretical issue is related to the fact that all the possible solutions to the problem focused on obtaining developable stripes from pairs of curves supposes, is finally defined and delimited by determining the geometric place of the points that both tangential developable surfaces share.

At this point is interesting to highlight the point that both tangential surfaces are developable surfaces and the direction of the tangent vector coincides with one of the principal curvature directions at the point on the surfaces. In this special case, this one which counts with zero value of gaussian curvature. In other words, that direction is the same that the tangent to the osculator circle of infinite radius. If we think on the developable surface as a parametric one we can easily compute both principal directions as u-v isoparametric curves. This way of proceeding simplifies absolutely the difficulties that represent the question of dealing with tangents to the curves that represent an unfulfilling question in our previous approaches.

From the geometrical point of view, the weakness of the system is closely related with the relationship between both curves and their relative curvature. It means that there are some unavoidable geometric constraints that establish the limits to the geometric developments.Then the main objective of tracing developable strips suitable to be fabricated is imposed by the pure geometric reality and we can affirm that along some special zones absolutely developable strips from the geometric point of view are impossible to be obtained. From this point, it is necessary some kinds of adaptative approaches to confer construct validity to the theoretical proposal. The delimitation of this zones and characteristics of the curves and its relationship as well as the way to solve this special cases and discontinuities are subject to continuous approaches and will be considered in future works.

RESULTS

As it has been presented above, The main focus of this theoretic development follows a practical objective that can be materialized in Architectonic constructions. In this way, several physical models have been built in order to validate the processes. Some of them finished only at prototype scale (figure 4) and other ones at real scale by means of different small pavilions.

Figure 4
Small prototypes of free form surfaces adapted by using convolutas

Figure 5
Cactus pavilion. Santiago of Anaya, Mezquital Valley, Mexico. Convolutas, Developable Strips made of 3 mm. plywood.

Cactus pavilion

The project is defined as a double-sided statement. On the one hand, it presents a real constructive experience regarding experimental lightweight Architecture. This experience involves in-depth research around Advanced Geometry, Digital Fabrication and ephemeral architecture applied to heritage, along the lines of low-cost construction and environmental concerns. On the other hand, the proposal advances in the exploration of adaptive envelopes, reactive materials, and the continuity of geometric development towards the use of developable and responsive surfaces in Architecture.

The **Cactus Pavilion** (figure 5) is a real wooden pavilion developed as roving interpretation centre of the Architectural & Natural Heritage Rescue Project of Santiago de Anaya, Mexico.

The pavilion is a stand-alone architectural object that, by itself, strives to represent the values of the project and its connection with the landscape and the environment. The shape of a cactus was proposed as a biomimicry architectural form, inspired by an endemic species of this valley, Echinocactus plathyacanthus, and its 'cristata' forms.

Figure 6
Globoide pavilion. ETSIE Sevilla. Revolution of a circle non-coplanar with the axis adapted by using convolutas.

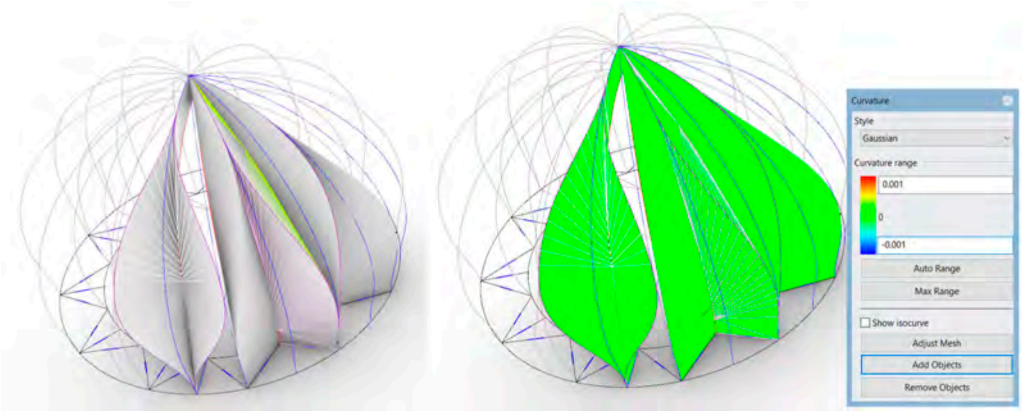
The installation uses natural materials and a sustainable manufacturing model, which has been developed as a lightweight construction, with an easy assembly process. Likewise, the architectural installation is innocuous where environmental protection is concerned, leaving no traces or residues in the placements. The pavilion was designed by employing CADCAM and parametric tools and was mechanized by using a common CNC milling machine. The architectural installation is made of 4-mm-thick plywood strips that, once arranged, bent, and joined together with nylon cable ties, forms a self-supporting structure. The design, construction and assembling of this pavilion has been carried in diferent spaces all over the world, Universidad de Sevilla, Spain; Universidad del País Vasco, Spain; and UNAM, Mexico. This circumstance has led to arrange a methodology that also bears in mind the idea of global design system while the materialization of the ideas remains locally. In this way, we have taken advantage of the possibility that increasingly global knowledge transmission offers nowadays.

The proyect has been designed by Department of Graphics Engineering, ETSIE, of Universidad de Sevilla (Andrés Martín Pastor); in collaboration with FabLab Donostia EHU-UPV Donostia, Spain (Francisco González Quintial). Cactus Pavilion was awarded with a Honorable mention at __Laka-React Competition 2019, where complete credits can be consulted.

Globoide Pavilion

Globoide Pavilion is an experimental pavilion (figure 6), the result of the Teaching Innovation Project entitled: "Geometry and creativity. Design, Manufacturing and Assembly processes of Experimental architectures in University Education". This project involved Universidad del País Vasco (Fablab Donostia), Universidad del Litoral, Argentina; Universidad de la República (Uruguay); and it was conceived and coordinated by Department of Graphics Engineering, ETSIE, of Universidad de Sevilla. The general proposal consists of approaching the phases of design, digital fabrication, and assembly of a wooden pavilion by means of Descriptive Geometry and with digital tools. The academic project is articulated applying a theoretical-experimental model that is verified through the realization of small-scale prototypes and, finally, with the assembly of the full-scale architectural installation. This experience its an advance of previous experiences carried in the context of international workshop (Martín-Pastor, García Al-

Figure 7
Parametric model. Obtention of the developable strips following imposed edges. The Gaussian curvature analysis shows the developability of these strips.



varado 2019)

The shape of The Globoide is generated by the revolution of a circle around an axis that should be non-coplanar, otherwise if both of them are co-planar the revolution surface generated is well known as thorus. The research objective of this project is focused on the evaluation of the system on this kind of special shapes where the gaussian curvature varies from one part to another. Actually constitutes more an approach to the adaptation of double curvature surfaces by using devolopable strips (convolutas) than an adaptation proccess to developable forms between a pair of curvas. Nevertheless, the process employed in this case is strictly the same with slightly different nuances. In this case the input values are circles on the thoroidal surface and the scope of the method, as has been signed above, reach some difficulties around the zone where the two curves cross. Purely, from the geometric point of view, the concept that is embedded in the core of these cases is based on the use of Convolutas following the development exposed above. (figure 7) In this way an absolute parametric model was developed where the curves that define the edges of the strips were well defined and at the same time they could be easily adapted by varying slightly the parameters that define them. Progressive approaches to the form allow to deal with the form of tracing the appropriate forms of the strips in order to be fabricated.

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Before affording the real construction, at lower level we proceeded to physically check the suitability of the system, the accuracy of the designing results and the behavior of the material we are planning to use by constructing proportional prototypes at minor scale. (figure 8) In this way, the differences between the prototype and the real building can be foreseen and the troubleshooting can be anticipated as far as construction issues are concerned.

This phase of the work is also based on the structural analysis of the material and its behavior like bending active strips by using parametric structural analysis software, in this case Karamba (figure 9), which is a Finite Elements Method modeler that al-

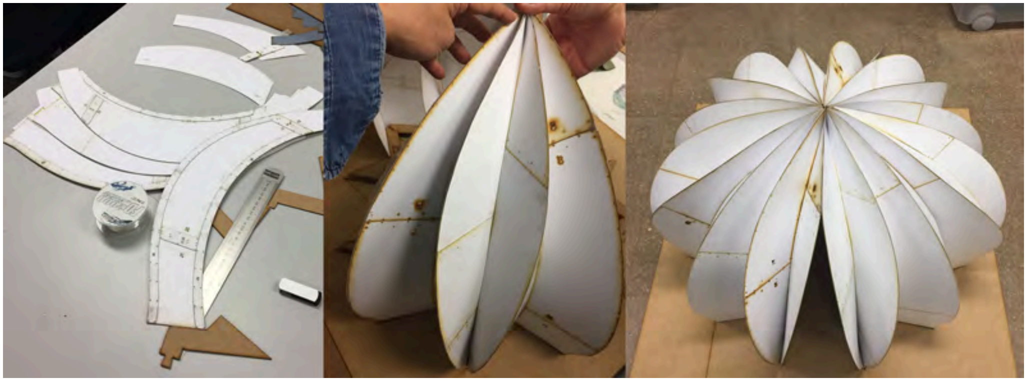

Figure 8
Prototype made of cardboard at 1:5 scale

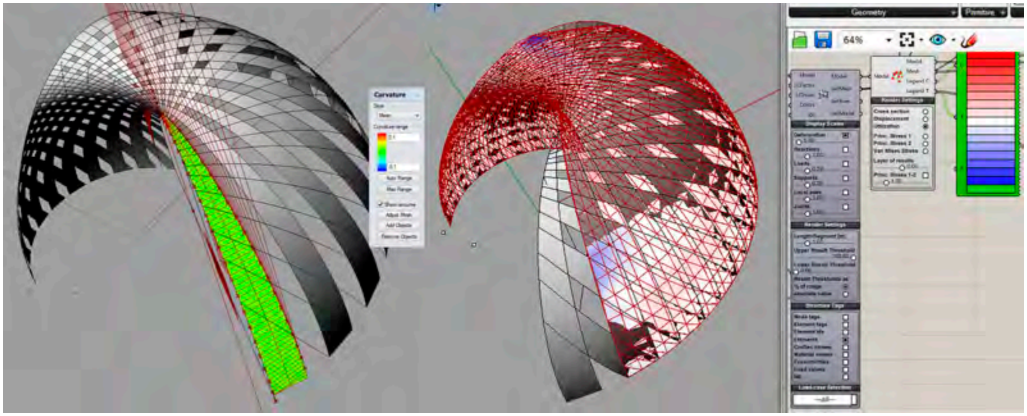

Figure 9
Geometric and structural analysis of the surface.

lows the graphic analysis into the parametric model. In this way, all the process is developed inside the same graphical environment and is produced by using the same chain of algorithms written.

CONCLUSION

The application of the method demonstrates to be satisfactory in the analyzed cases. The systematizing of a process formulated in the classic theory of the Descriptive Geometry -Geometry from the Graphic- by means of a new algorithmic process allows to validate first the theoretical general method and to allow its application in such a way that was turning out to be impossible before the generalized use of digital tools.

As is commonly know, the use of developable surfaces to model free surfaces or double curvature surfaces has an important application in different areas and specially in Architecture so it supposes, apart from other interesting mathematical approaches, a suitable development considering it allows the use of the traditional materials without the need to use much more expensive curved processes.

Though we are working at the jump from the prototype to the real construction elements, nowadays this constitutes one of the most exciting future ways of research. Moreover we have to bear in mind that we are working with CAD software and simultaneously more and more we are getting used to digital fabrication hardware as 3D printers, laser cutting and CNC machines.

We speak about prototypes at major or minor scale, not models, in the prototype we can already anticipate and foresee the behavior of materials in relation to the way they are arranged and assembled. The prototype has a value in relation to purely formal model, we have seen the results in terms of tolerances, movement, adaptability of certain light materials and conclusions difficult to predict theoretically.

Regarding geometric concepts of the system we can indicate that new routes appeared are opened in the research and adaptation of the theory used in reference to the developable surfaces where we are mainly focused. The extension of this paper shall prevent the exposure of the entire system, there are located some new directions and spaces to enhance the system, overall in determining the gaps of the system. The exhibition of the rest of results due to this research line will be matter of future articles.

Finally we can add that we are profusely using and teaching the obtained developments in Advanced Geometry through the academic community by this connections between virtual and physical realms. In this way we can match the theoretical knowledge with the physical manufacturing and construction of architectonic elements through the use of new tools framed into the 4th Industrial Revolution.

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Contemporary Architecture between Research and Practice

Experimentations in Digital Wood

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This paper is a take on contemporary works in wood designed with parametric softwares and seen from an academic and professional point of view. The knowledge about digital wood developed through Digital Fabrication Laboratories has proved to be effective but with certain limitations when used for real constructions. In fact, translating the freedom of building temporary architectures -which is usually one of the ``learn by doing'' activities of design studio or workshops- into wood architecture that respect all the constraints of real construction is a challenge. This paper shows several experiences where innovative ideas developed through research have been applied to temporary pavilions and real constructions in Japan, Italy and France.

Keywords: *Parametric design and fabrication strategies, Pedagogy and Practice, CNC and Woodworking Technology, Wood complex surface*

INTRODUCTION

Computational software and digital fabrication technologies are contributing to the transformation of the construction sector which, until the 20th century, was rather static and closed.

Currently, architects, designers and engineers have to face increasingly complex design requirements which leads to the question: how do practices acquire the ability to do so? There are at least two ways: either by developing applied research on their own or by including students trained in complex design. These are the two most viable methods to integrate research into work and to prepare for the changing form of practice in architecture. However, once this conceptual framework has been integrated into practice there are some issues left open such as budget limitations, building code regulations, technical constraints, durability, expertise and machines used by the construction companies.

This paper considers contemporary works in wood seen from two different points of view: academic and professional. It builds upon several years of academic research experience at the Kengo Kuma Lab of the University of Tokyo, at the National Research Center (CNRS) in Paris and at the faculty of architecture La Cambre Horta, Université Libre de Bruxelles. The author is one of the founders of LAPS Architecture, an office based in Paris characterized by an applied research approach to architecture. In the past years, LAPS Architecture has developed a specific language through the integrated use of parametric design and the employment of different materials for private and public projects of different scales. Through the study of different case studies, the goal of this paper is to show the limits of the integration of research into practice.

BETWEEN PEDAGOGY AND PROFESSION, RESEARCH AND PRACTICE

Efforts in establishing research in the use of digital wood in architecture commenced in 2009 with the first courses at the University of Tokyo introduced by Kengo Kuma and related seminar courses that focused on a parametric approach to different materials including wood. Full-scale constructions constitute an essential element of research by design in these studio courses. Besides design studios, the study of architecture, materials and structure is often reinforced thanks to targeted activities such as summer schools and hands-on workshops.

Research by design as a mode of inquiry had its own particular modalities and one of the most effective strategies is to design and build a small pavilion. Building a pavilion presents several positive aspects because it can be done at reasonable costs, it is ideal to test new materials and it can be built by the students themselves. Learning outcomes are very positive because, thanks to these activities, students get a first concrete experience in the physicality of construction and test all the aspects of translating ideas into real projects.

Research at work

Among small-sized architectural offices, it is not common to do research because it is time consuming and not immediately economically sustainable. According to Hensel (2016), practices interested in research develop a knowledge that "involves specific ways of integrating architectural education and research, in particular research by design, to support the development of related knowledge, concepts, methods and frequently also the production of reliable empirical data, engaging real-life design problems and seeking interaction with practice". LAPS Architecture has invested in research activities to create a comprehensive approach to architecture and has focused on the combined use of digital tools and materials, such as wood and raw earth, integrated in the construction of private and public buildings.

For the author, the knowledge about digital wood developed in academy has proved to be effective but within certain limitations when used for real constructions. In fact, translating the freedom of building temporary architectures -which usually is one of the prerogatives of architecture built at university- into wood architecture that respects all the constraints of building codes is a real challenge. The research at LAPS Architecture relies on a team of usually one to three people according to the size of the mission. The work is organized around two different types of projects: 1) basic research based on form finding and material testing, and 2) oriented research aimed at solving real projects. Basically, on one hand there is a research for aesthetic pleasure of searching for new geometry, shapes, materials, assembly logic and structures. On the other hand there is a research oriented at solving concrete constructive problems.

The results of research based practice

The paper describes how knowledge developed through academic research is increasingly integrated into a small sized architectural practice on different projects sizes ranging from small to large. The article is organized diachronically which is significant in that it addresses different projects and resourcing requirements that are enabled by specific project sizes. Scale determines the type, scope and modes of research of each project. With the aim of experimenting the use of wood in contemporary architecture, the projects covered include: a tea house, a shelter for archeologists, a partition and shelving system and the facade for a public building.

RESEARCH: BUILDING SMALL PAVILIONS AS A STRATEGY

A small pavillon does not require significant economic investment (often a private sponsor or a research fund cover the expenses) but it is an invaluable tool to advance applied research, in testing new forms, materials, performances or assembly techniques. There is a rising demand in students wanting to participate in hands-on experience where they are involved in the translation of concepts into reality.

This paragraph describes two pavilions, which were the output of two workshops held respectively at the University of Tokyo in 2011 and at the Unesco Heritage site of Agrigento in 2013. The workshops were organized with the following structure: two universities invited, a topic linked to culture, a pre-defined budget, a two-phase period including design and construction, wood chosen as main material and use of parametric software and digital fabrication.

Approach and Practicability of Parametric Design and Digital Fabrication

The two workshops provided a point of reflection within the academic setting to consider the consequences of computational design when applied to the physical reality of making, rather than stressing too heavily on the form-finding aspects of computational design. Engagement in a continuous process leads to a constant feedback loop between the software, material characteristics, and contextual considerations. The parametric tool allows for the input of an almost infinite amount of information, producing mathematically logical, countless variations during the process, but it obviously cannot determine any hierarchical design decisions. Matsukawa (2007) dissects the differences between conventional design process versus the generative model, where diagrammatic process models between environment, architect, building, user, and other basic criteria such as building codes, operate differently and it is illustrated in examples including linear model or partial feedback loop model. One of the most complicated process diagrams -where series of algorithms are employed- leaves the architect with the "question" without a definite answer.

Each of the pavilion's physical presence and their feasibility on multiple levels were evaluated and considered throughout. The process also assessed the technology employed and the highly sophisticated elements that can be produced, whilst relieving participants, who were inexperienced in construction, of some issues including protection from weather, foundations, and structural stability over an extended period of time, thanks to the temporariness of pavilions. It also encouraged material experimentation, intuitive predictions for structural elements, and a trial and error approach in detailing and assembly. The shift in focus from satisfying the public at large to an increasingly personal scale gave an ideal opportunity to test these digital tools. The small scale of the tea house and its function, both of which are deeply rooted in culture and its sensibilities, may not produce monumental visions single-handedly. The potential for individual insights to be optimized by the use of parametric tools and processes pointed to a direction where the framework of culture can serve as a starting point for selective optimization. Design has evolved alongside technology in a mutually beneficial relationship.

DIGITAL TEA HOUSE WORKSHOP

Held at the University of Tokyo, together with Columbia University GSAPP, Digital Tea House was a joint workshop with the aim to design and build three pavilions for hosting tea ceremonies. Issues addressed in the three-week workshop ranged from applications of computational design, interpretations of tradition and culture, structural stability, to practical solutions for quick physical materialization within limited time and budget. The workshop was divided into two sections. The first part introduced computational logic and concepts, which led to the second part where explorations relating to the Japanese tea ceremony culture served as a pretext for further exploring digital design and fabrication. Three teams, each comprised of 6 to 8 members, ultimately produced three full-scale tea houses to test out their concepts, methodologies and materials. Several elements served to make comparisons and analysis during the process and later in two distinct out-

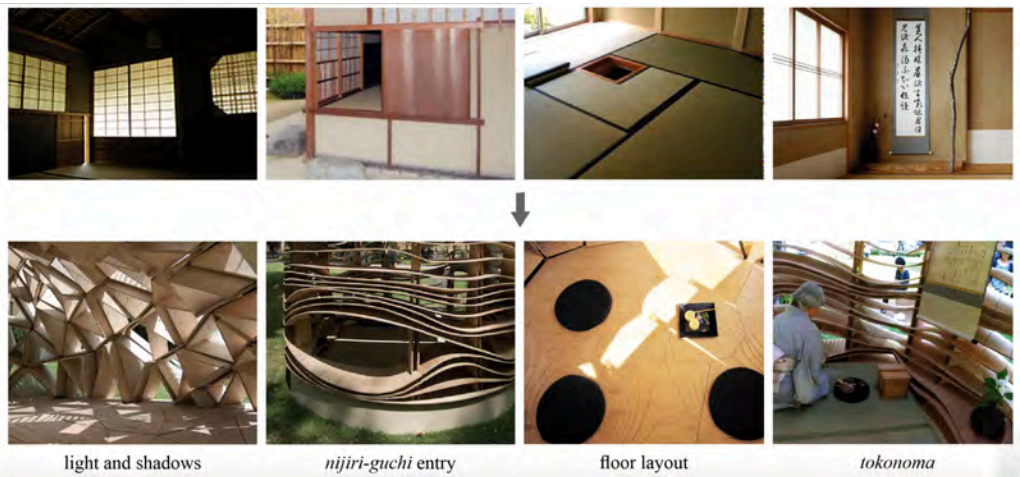

Figure 1
Traditional elements, above, were used as inspiration to create contemporary interpretations

comes: baseline for common software (Rhinoceros and Grasshopper), principal material (50 sheets of 9mm and 12 mm thick 3x6 plywood), fabrication method (CNC routing), and budget (of approximately 1,500 €, per team, excluding plywood and CNC fabrication costs). The output of the workshop clarified that, firstly, parametric processes are not contradictory to traditional cultural principles; and second, how traditional elements of the tea house can be decoded and formally reinterpreted through parametric design.

Tea house as a cultural backdrop

In the 16th century, the Japanese people gave life to a new culture which consisted of elements such as the tea house, *'Sukiya Style Architecture'* and the *'Wabi-Sabi'* aesthetic of transience [3]. At the time, the 'Tea House' thus represented an avant-garde type of architecture. Stemming from the use of the body as a point of reference, the tea house evolved into a microcosmic situation where host and guest(s) meet and, at the same time, an intellectual device through which one is made aware of the natural phenomena occurring outside. Moussavi (2006) writes: "architecture needs mechanisms that allow it to become connected to culture. It achieves this by continually capturing the forces that shape society as material to work with it. Architecture's materiality is therefore a composite one, made up of visible as well invisible forces." The traditional tea house is composed of a variety of elements, including shoji screens or bamboo slats that serve as light filters that underscore gradations of light, a small wooden sliding door at nijiriguchi entryway, tatami mats that signify where one may sit, and a recessed alcove tokonoma for hanging scrolls and flowers (Fig.1).

From Context-Neutral to Context-Aware Design

How can we build a bridge between the digital environment to the physical environment in which we live? First, we addressed the consequences of the designs - how every part should be considered for its strength, weight, its assembly sequence, and surface treatment. There are also questions regarding appropriateness and scale of design, which often cannot be resolved in the isolated modelling phase. How to reconcile disparities is one of the biggest challenges in the design process; this workshop used the cultural function of the Japanese tea house as a starting point to address the gap. The often scale-less nature of design through scripting is applied via a traditional set of rules, such as the prototypical 4.5 tatami-mat scale of a tea house, to be physically implemented.

The process of computational design and fabrication can amplify complexity as desired, but perhaps more intriguing are considerations on what new values can be extracted from the combinations of culture, tools, and materials, and what sets of cultural values are left behind in the process of translation, or decoding. The development process from context-neutral idea to context-aware architecture calls for multidimensional views, and the deviations apparent in the outcomes each show different approaches and emphasise the problem of the rationalization of traditional aesthetic sensibilities.

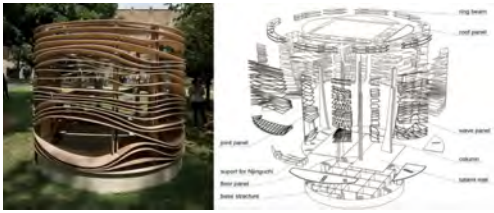

Figure 2
Pavilion
Nami-no-Ma

Pavilion "Nami-no-Ma (Space of Waves)"

Guided by strong aesthetic characteristics from the tea ceremony, the expression of the beauty and imperfection of nature inspired by the tea bowl is translated to plywood, which surrounds the basic 2-tatami traditional layout of the interior space (Fig.2). The initial concept was drawn from the slightly irregular traces left from the process of throwing the tea bowl on the potter's wheel. The bowl used in Japanese tea ceremony favored controlled imperfection in the aesthetic of yuragi and yugami. Yuragi is the slightest warping often from the uneven pressure of the kiln, which later developed into a more as deliberate and artistically restrained distortion of yugami. Pavilion Nami-no-Ma boldly translates the phenomenon of yugami in the same calculated manner as the ceramicists of the past, with every layer of plywood by taking advantage of the CNC router. Efforts to create a natural and flowing form from the 3-axis CNC routing, which is a flat surface fabrication, pushed for experimentations with half-depth grooves in specifically calculated patterns on the 9mm plywood. The key challenge was in achieving the desired bend in a continuous curve following a circular geometry of the plan. Enabled by close communications with CNC router operators, tests initially began with grooves of different depths and stitch patterns of varying lengths. The triangulated grooves eventually proved to be the ideal solution for 3-directional curves to be fixated on site, whereas perpendicular grooves only enabled 2-directional bending per panel.

Tea houses typically offer a limited level of openness to the outside. In this interpretation, the varying thickness of the wall becomes the boundary between the tea ceremony taking place inside and the surrounding nature, while the views are controlled by the density and bending angle of each layer. The undulating waves also facilitate the functions of tokonoma and nijiri-guchi, where the largest opening in the pavilion is structurally reinforced beneath the lower curvature to support body weight.

Figure 3
Detail of the joint
for solving the
double curvature
and the zig zag
grooves

A PAVILLON FOR ARCHEOLOGISTS IN AGRIGENTO, ITALY, 2013

"Architecture X Archaeology" is a co-joint workshop held in 2013. Students form the University of Tokyo, Politecnico di Milano and Università di Palermo explored the design and construction of lightweight, temporary structures to shelter excavation works otherwise exposed to the weather.

The workshop was divided into two parts: a preliminary part, 45 days duration, took place at each university. The second phase, 7 days long, took place on site. The workshop focused on the complexity of designing within archaeological sites such as anchoring to uneven ground, run-off and collection of rain water, transportability but also applications of computational design, structural stability, and practical solutions for quick physical materialization of ideas within limited time and budget.

Figure 4
The Molecular Shelter near the Tempio della Concordia

Molecular Shelter: a temporary shelter for archeologists

While respecting the local context, the Molecular Shelter design reinterprets a concept borrowed from-Japanese traditional culture. It takes inspiration from the To-Kyou bracket system found in traditional wood Japanese temples, where the roof plays a prominent role. It is a stacking structure composed of wood materials and it enabled architects to design flexible plans. The shelter meets the requests to have a shelter with a roof as large as possible, designed to carry the rain as far away as possible from the excavations, movable from site to site, and with the possibility to be set up again in different locations and with minimum surface area at the column base. The used bracketing system presents an intrinsic elasticity, which lessens the impact of lateral forces by acting as a shock absorber. The position of the columns can be changed thanks to a grid ceiling-structure (Fig.10). The shape of the inclination of the roof - to evacuate rainwater - is borrowed from Tempio della Concordia, so to have a direct reference to existing forms in the landscape. The shelter is light, easy to fabricate and assemble in a reasonably short time (it takes one day and four people), movable, adaptable to the site, and modular. The structure is designed to allow the archaeologists to move the shelter without any help and to hang their working tools.

The shelter is composed by a joint system of 4 small struts, with constant section, bound along both X and Y direction beams with M6 screws. The screws add resistance against rotational movements. If requested by particular site conditions, columns can be positioned at different points of the grid and have different heights. The structure weighs around 100 Kg, and can be easily moved by four people. The shelter is made of local pine trees, cut and assembled with 1500, 6mm size screws. It took five days to cut and prepare the pieces and one day to assemble them. The final cost of the pavilion amounted to 1,200 €.

Programming was developed through Rhino, Grasshopper and Python. This made it possible to organize the exchange of information and optimize the calculation which enables parametric changes. In particular, the use of parametric software proved to be essential for testing different size and arrays of the grid structure, structure thickness and weight, materials length and number of elements used. As for the fabrication, a hand-made easy fabrication system was preferred, which demands only simple holes by drilling and screwing instead of sophisticated machinery. Due to limited vehicular access to the archaeological areas, it has proved strategic to use transportable lightweight tools.

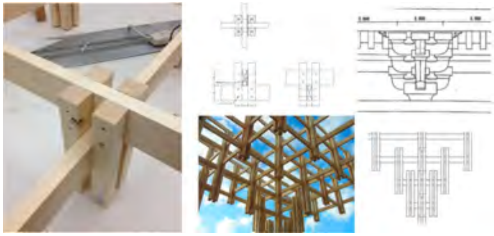

Figure 5
Joint detail and mock up

PRACTICE

Increasingly complex design requirements demand practices to acquire the ability to cope with them. LAPS Architecture has been developing applied research as a tool for experimenting on its own by conducting applied research and by including students trained in complex design in its team. As written above these are the two most viable methods to integrate more research into real work and prepare for the changing form of practice in architecture (Samuel 2017). Experimenting has some costs, however, in the case of LAPS Architecture, the investment in research is a calculated risk that is bearing good results in terms of integration of research into practice and it defines the identity of the office. Issues such as budget limitations, building code regulations, technical constraints, durability, expertise and machines used by the construction companies involved in the projects are decisive for building an architecture with an advanced level of complexity.

This paragraph focus on how the use of advanced digital modelling solutions have been translated into solutions that respect all the constraints of building code and different parameters such as structural soundness, fire risk prevention, standard assembly logic, certified materials, budget and time constraints.

Architecture practices experience a paradox: to work they need to build projects, to build projects they need to have already some built references, to have references they need to build. But for a young architect there are not many possibilities to build since the practice does not have references. One solution is to design and build temporary installations which is a good strategy to test ideas, materials, etc. But once a practice gets a project, usually, there is no time to experiment new solutions, because the different phases of a project are very strictly regulated by public rules regarding the due date for delivery i.e. for a project such as the recreational center for children discussed later in this paper (a 1.000 sq. m. project), the schematic design was limited to four weeks, the design development to four weeks, construction documents to eight weeks. This means that there is a very limited amount of time to experiment, test and analyse new ideas: basically, quite often, an architect usually prefers to rely on concepts, materials, technologies he/she already knows which are possibly certified and normed. All delays are subject to economic penalties that an architecture office does not wish to pay just for the sake of doing an experimental design. Basically, to avoid risk is to use standard protocols, forms and materials and one of the possibilities for small size architecture practices is to use ongoing, personal research and try to integrate the knowledge developed when a real possibility arises. It does not mean that research previously developed is adjusted randomly to a project but the sole fact of having a research mindset helps to develop potential solutions faster. For LAPS Architecture office investing in applied research represented a way to diversify its business and to define its identity and style. Architectural constructions are often quick in terms of drawing phases and slow in construction, impeding an immediate feedback between ideas and reality. On the contrary, small projects or installations offer architects the possibility to test ideas more immediately. The strategy used by the office is clear: instead of investing only in medium or large size architectural projects, the partners of the office decided to stimulate potential economic gain from interior and product design. There are some legal protocols such as the so called "ATEx" or "Appreciation of Technical Experimentation" that transfer the research risks onto the contractor and make it easier for architects to promote innovation and changes in regulations. In French Building Code regulation there are several classes of public building that demand different types of wood according to different safety and risk factors such as the number of people allowed in a building or the number of floors. These factors define the class of the wood for structural loads and fire prevention. For structures and facades there are different classes of wood allowed. In the past years there has been an increasing interest in wood construction and accordingly new rules and limitations have been updated to current demands for safety and risk preventions. For those architecture offices integrating research into practice is even more challenging because they have to manoeuvre within this framework in constant evolution.

X.ME SYSTEM

The X.me project is an investigation on structure, assembly and fabrication process in order to produce a customisable modular system for interior design. Developed firstly as an academic research, the X.me system evolved into a product thanks to several prototypes built in real contexts such as the Norman Castle of Favara, the Hotel de Gallifet in Paris and Sasebo in Japan. Resulting in a redefinition of the classic chain designer-maker-distribution-client, the X.me system is modular and flexible and easy to configure (Liotta 2016). The X.me system is reduced to its bare essentials which allows everyone to assemble it without using nails, bolts or glue. The system is self standing and presents a solid structure, it is easy to assemble and disassemble resulting in a reversible system. The intersecting elements of a grid pattern has been extruded to create customized elements for different interior design needs such as partitions, bookshelves, sitting spaces, benches and tables. Interestingly, the orthogonal rigidity of the grid patterns permits a great degree of diversification on the Z axis. The system is composed of customised panels made of different materials such as wood, MDF or PVC. Horizontally or diagonally cut, the panels are then combined and assembled manually. Customized elements cut by a 4 axis CNC machine are assembled by using extruded aluminium joints of different size. An online configurator allows for real time customisation, shopping and delivery. The system offers a different approach to design and gives the possibility to the customers to design and order online a customised solution of different products directly from the maker thus reducing the cost of production, stockage, promotion and transport.

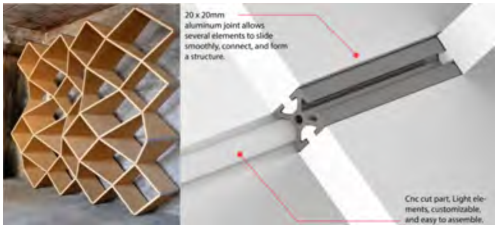

Figure 6
A configuration of the X.me and the aluminum joint detail

X.Me Design and development

The development of the X.me system is here shown through the analysis of two installations -at the Norman Castle of Favara and at the Italian Cultural Institute in Paris. Besides showing different formal solutions, flexibility and adaptability, at the same time the two installations underline some limits of the system. While it has proved to be very intuitive to design and simple to assemble when composed of a limited number of elements, it still needs improvements for medium and marge scale projects due to the difficulty to put in place the upper part of the system. The difficulty is due to the fact that even slightly uneven floors affect the assembly by deforming the grid through its weight. Because of the weight, the geometry of the grid varies infinitesimally but enough to impede a smooth assembly of the system. To solve this issue, the elements were cut thinner than the aluminum joint size, however some elements needed to be hammered to slide into the joints. This proves to be a major problem for commercialization, because only specialized workers can assembly the system. Another solution is to send the furniture already assembled, but this will increase the shipment costs because it will occupy more space than when it is sent disassembled.

In the project for the info point center of the Norman Castle of Favara, after testing different materials such as wood, plywood and MDF, the last was chosen. Because of the unpredictability of the direction of its fibres, wood proved to be the least performative material. MDF -being a composite wood material-presents an homogeneous fibre direction which is indispensable for the elements to easily slide in and out from the aluminium connector. In this first project, the modular system integrated different programs such as tables, benches, partitions and shelves.

In conclusion, several installations served to test as many issues as possible regarding functions, program, assembly, materials. The knowledge collected helped to finalise an online configurator by which the X.me system can be designed directly by potential customers. Customers get an immediate price and delivery time. Once the order is finalized, the drawings are processed through Rhinos and Grasshopper and then exported and arranged on panels and ready to cut by CNC milling machines.

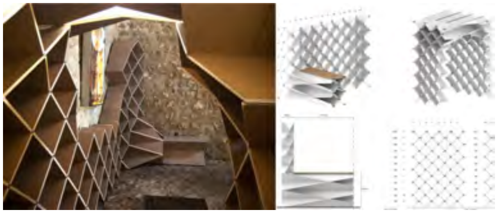

Figure 7
Installation of the X.me at the Norman Castle of Favara and fabrication drawings

RECREATIONAL CENTRE FOR YOUTH IN CANTELEU, NORMANDY, FRANCE, 2016

Figure 8
The facade with flat and curved lamellas

The project for the recreational centre for children and young people in Canteleu is located in a depressed area of Rouen suburbs. The rate of unemployment of this area is around 25% (two times the national rate) with a presence of nearly 60% of social housing built in concrete. The mayor required that the recreational centre for children and young people 1) included a certain attention to aesthetics as a positive message for the youth of the city, and 2) that the building had to be in wood for it is a sustainable material, and thus bring a positive message in opposition to the existent concrete landscape of the town. The project includes in its architecture these two elements: a building which is recognisable thanks to a wood facade shaped in form of a wave which represents the energy and dynamism of the youth of Canteleu. The wooden wave is one of the possible results of a research on how to generate an iconic architecture by mixing standard and non-standard elements (respectively flat and curved lamellas) to reduce the costs of the project.

Recreational Center Design

Whilst the structure of the building is made in cross laminated timber, the facade is made in pre-coated pine wood. The facade was partially pre-cut at factory and assembled on site by carpenters.

The design includes 40 mm wide lamelles of wood which alternate two flats one and a curved one. The distance between the lamellas is 10 mm, which is the maximum distance allowed by the so called DTU-Dossier Technique Unifié (Unified Technical Regulation). The original project presented a distance between lamellas of 40 mm with 40 mm wide lamellas. The idea behind the design was to minimize the use of wood by having a certain distance between lamellas. The fact that new regulation for public building was changed between the competition phase and the construction phase demanded the design to be updated to comply with the new rules.

The design of the wave on the facade was defined by some spline lines that change direction according to the facade openings. For the construction, initially only the flat lamellas were positioned and fixed on a horizontal substructure composed of 4 battens distanced 1 meter from one another. Subsequently, the curved lamellas were nailed to the substructure. Originally the curved lamellas were supposed to be more than 150 mm deep in the highest point, but there are no standard nails long enough to fix such a deep element on the supporting substructure. Therefore, the thickness of the lamellas had to be adjusted to 50 mm. This affected the initial design making it more flat. In the DTU there were no indications concerning the depth of wood in facade, however the design changed for technical constructive reasons.

Concerning computational aspects, programming was developed with Rhino and Grasshopper.

This did not help the exchange of information and optimization with the construction company, since they only used Cad software. The use of parametric software proved to be good for testing different size and arrays of wave design, materials length, thickness and number of elements used. As for the fabrication, a mix of CNC mill cut elements and handmade fabrication was used. The overall result is acceptable but it respects the original design only partially. In fact the curved lamellas were resized and since they were hand cut on site do not exactly correspond to the design.

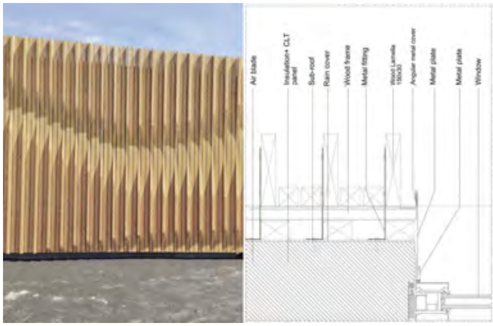

Figure 9
A detail of the facade and a technical drawing

CONCLUSIONS

Translating the freedom of building temporary architectures -which usually is one of the prerogatives of architectural design at university- into wood architecture that respects all the constraints of real construction proves to be difficult because of several parameters that must be taken into consideration.

The use of parametric design can, at times, promote a tendency where its users can easily produce forms too complex to control with little regard to issues not only of structure and feasibility but also economy, society or culture, in part due to a fascination with new forms. The chapter makes clear that constraints including structure, material, budget, time, assembly, site, and function help avoid the risk of designs that are impossible to be realized. When parametric design is integrated into a process within a framework of real-life constraints, its advantages are beyond mere stylistic choices or visual effects. Often, as we are limited to the constraints of borrowed code, the majority of architects are forced to limit their imagination within the prefabricated pattern of existing protocols. In a way this situation has started to improve with the introduction of custom scripting where architects can tweak the limitations of their tools.

This paper clarifies that 1) the democratisation of combined use of digital and fabrication tools have made it possible to conceive and realize complex design with limited budgets whilst respecting the building code, 2) the design of the projects here discussed has evolved alongside technology, within a mutually beneficial relationship 3) integrating research into practice is a way to try to make better buildings, that are appropriate to theirs users, clients, context and time.

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Customizing Mass Housing in Brazil: Introduction to an Integrated System

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The current work presents an original parameterized wood frame system, a computational simulation of its structural performance and preliminary results of its digital fabrication and assemblage process. The project follows the concept of integration between CAD, CAE and CAM systems, aiming at the automation of the processes that make mass customization of social housing in Brazil practicable.

Keywords: *mass customization, social housing, parametric and algorithmic design, simulation, prediction, and evaluation, digital fabrication, building system*

1 INTRODUCTION

Since the migration process from the countryside to urban areas during the industrial revolution in the 19th century, social housing became a pertinent issue in architecture (DUARTE, 2001). Currently, the housing production is still extensively based on the Fordist concept of mass production, which uses the standardization of components and the systematization of the manufacturing process. Although housing mass production using such methods has been important in different contexts throughout history, the consequent lack of personality of housing raises questions about its quality as it does not attempt the necessities of the residents (BENROS & DUARTE, 2009).

From the second half of the 20th century, the growing needs of consumers for more personalized goods and services, in addition to advances in computation that arose during the same period, led to changes in production methods. Thus, the computational revolution has affected a variety of industry fields, enabling high levels of product and service personalization to be achieved on an industrial scale. Using these new computational technologies, large industries were able to connect instantly with consumers and apply methods that are "sufficiently adaptable systems to produce a wide spectrum of different forms" (CELANI & PUPO, 2008). One of these methods of production is known as mass customization, which is a process of manufacturing goods that allows the high level of product customization on an industrial scale.

Among the premises for mass customization, the automation of the design process, the manufacturing process, and the assembly process through tools that are economically available are predominant (PINE II, VICTOR, & BOYNTON, 1993). The use of computational generative systems and digital manufacturing systems, capable of assisting the design and production automation process, can already be observed in certain areas of civil construction, that are looking for technological innovation. However, because of the characteristics of the final product, which includes its dimensional constraints, there are no economically available tools for the automation of the *in situ* buildings assemblage process. In South America, the situation worsens if taking into account that historically technological movements are usually delayed compared to those of developed countries in Europe and the United States (SPERLING, CELANI, HERRERA, & SCHEEREN, 2015). Therefore, a consolidated alternative for the construction of digitally fabricated buildings is the creation of alternative systems based on the division of the building into smaller pieces that can be easily interlocked (GRIFFITH, WILLIAMS, KNIGHT, SASS, & KAMATH, 2011). Nevertheless, some important criteria need to be considered for accepting such systems in developing countries, such as different formats of local cultural and social aspects embedded in the design of building systems, structural stability and safety, and the use of local materials (KNIGHT & SASS, 2010).

This current work aims at demonstrating the systematization of methods that led to the proposal of a wood building system for mass customization in Brazil, which incorporates freely selected aspects of Brazilian popular architecture with an interlocking system for ease of assembly and is capable of being digitally manufactured with an available technology in the country. The application of the system in a CAD, CAE and CAM environment and the integration of those three platforms aim at the instantaneity of its production.

The study seeks to contribute with answers to two questions. First, how to make the assembly process of mass-customized housing feasible, in short and medium terms, without having an available technology to automate the large-scale assembly process. Second, how to integrate CAD, CAE and CAM processes to make housing mass customization possible.

2 METHODS

A major goal of the research was to develop a building system for mass customization of housing in Brazil. To accomplish this goal three steps were taken: [i] design conception of the building system; [ii] automation of the design and production processes; [iii] verification of assembly process viability. Each of the methods to accomplish these steps is explained in detail in the following sections.

2.1 BUILDING SYSTEM DESIGN

The system design was developed based on the design for a manufacturing and assembly method (DFMA) introduced by Boothroyd, Dewhurst, and Knight (2010) (as cited in Celani, 2014). In this design method, issues related to the manufacturing process are considered during the initial conception of the product in order to facilitate its fabrication and assembly. Thus, during the design process of the building system, different variables that influence the manufacturing and assembly process were taken into consideration. First, a digital manufacturing technology was determined with affordable market costs and availability in the region. Then, it was defined that manufacturing must be accomplished by using a two-axis CNC laser cutter machine or a two-axis CNC router. Second, it was necessary to define the material to be used taking into account the following criteria in order of relevance: (i) possibility of management with the chosen machinery; (ii) affordability; (iii) local availability; (iv) local cultural acceptance of the use of this material in civil construction. Based on these criteria, reforested wood sheets were selected for structural use, which can be specified in different formats depending on the project needs, such as glued-laminated timber, plywood or OSB. Third, the assembly of the building system must be a systematic process. It means that even while constructing a varied spectrum of forms, the worker will be able to assimilate the execution of the assembly by repetition. Finally, cultural formal and functional aspects of Brazilian popular architecture must be considered and embedded in the design of the building system.

For the first three variables, analyses of case studies of building systems that used the same technology and the same material were carried out . It was concluded that the best method to design the system was the two-axis lateral contouring of the artifact to be produced (SASS, 2007). In this methodology, the three-dimensional objects that form the building system are sliced in two perpendicular directions and from the lateral contours generated by slicing, bidimensional objects are created. After the creation of the bidimensional objects, male-female joints are embedded in them. These joints are used to connect the two-dimensional objects that form the three-dimensional objects and to connect one three-dimensional object to another (Figure 1). For the fourth variable, aspects of traditional building systems of Brazilian popular architecture were analyzed (VASCONSELLOS, 1979). These aspects were then chosen to be incorporated into the design of the system according to their relevance and the possibility of application with the predefined material.

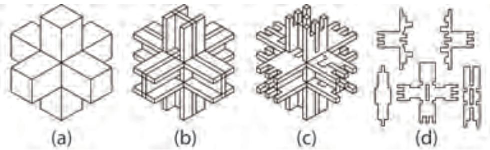

Figure 1
Building system creation process. (a) three-dimensional object is identified; (b) contours are made; (c) joints are introduced; (d) bidimensional objects are created.

2.2 AUTOMATION OF THE DESIGN AND PRODUCTION PROCESSES

Design and production processes were automated by the interoperability between CAD, CAE and CAM platforms. A design automation of the building system was possible through its parametrization in a CAD environment. The 3D computational modeling platform Rhinoceros and the visual programming plugin Grasshopper were chosen. The computational simulation of structural performance was automated by the interoperability between CAD and CAE platforms, which was possible through a plugin developed in C(#) language during this research.

2.3 VERIFICATION OF ASSEMBLY VIABILITY

For the verification of the assembly process a 1:1 scale prototype of selected parts of the system was fabricated. The digital fabrication of the connection samples was made in wood using a laser cutter. The 1:1 scale prototype made it possible to gather preliminary information about the ease of assembly and the climate influences on the integrity of the connections (metal connections or adherents were not used during this first stage).

3 RESULTS

3.1 BUILDING SYSTEM

The results of the work produced a wood building system capable of being manufactured by a CNC laser cutter or a CNC router. The generative system of the structure was conceived in two integrated scales. Firstly, bidimensional contours were fabricated from plywood sheets, then, these bidimensional parts were assembled to form tridimensional objects. The 2D and 3D parts are named “elements” and “components”, respectively. Both elements and components were connected by a single male-female joint system. The system incorporated local cultural aspects of civil construction into its design.

The component definition is based on the configuration of Brazilian popular building systems and uses the same structural system. According to Vasconsellos (1979), Brazilian popular building systems can be divided into four different parts: structure, flooring, walls and ceiling. From several structural system classifications analyzed, an autonomous structural system was selected. This type of structure is composed of structural frameworks and structural trusses that are independent of the sealing parts that conform flooring, ceiling, and walls. Therefore, because of the type of structural system selected, the structural components are independent of the sealing components. On the other hand, the sealing components depend on the structural components.

The building system was classified by four different families named “bars”, “connections”, “trusses”

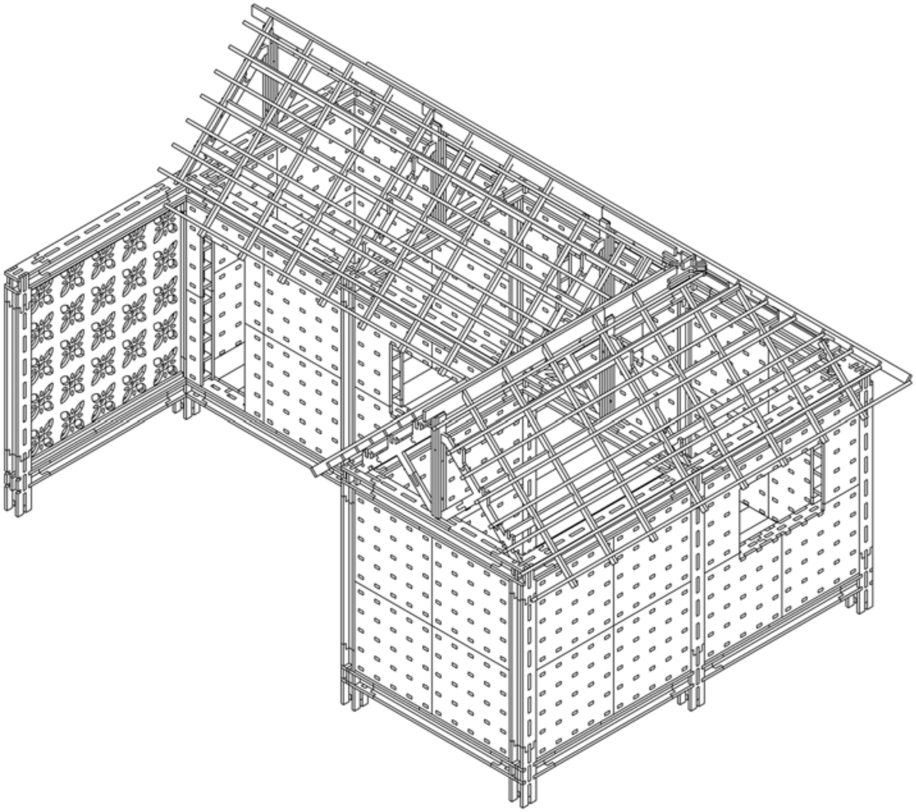

Figure 2
3D geometric conceptual model of the building system

and "sealings". It must be emphasized that the manufacturing and assembly processes were taken as criteria by this classification. Components are objects that originate from the assembly of bidimensional elements. Thus, although by means of structural analysis a structural truss is considered as a group of bars and connections, according to the classification defined in this study, trusses are classified as a specific component family. Each of these families can be divided by types, sub-types and instances. For example, the connections within the structure are classified as types according to their higher, intermediate or lower position. The subtypes of connections are classified according to the number of exit axes.

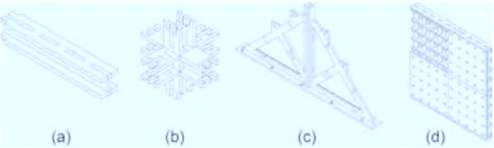

Figure 3
Families of components. a) bars; b) connections; c) trusses; d) sealing.

One of the goals of the proposed system is the ease of assembly, which is based on a single male-female joint system embedded in the elements, facilitating the connection between components. While in traditional systems analyzed the connections between parts vary according to their dimensions and the type of connection to be executed, in the developed system, independently of the type of connection, the action to be taken for assembly will always be the same.

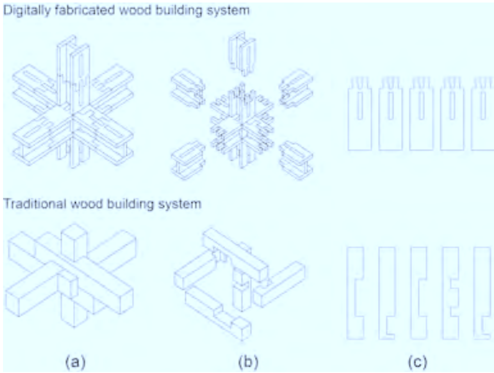

Figure 4
Comparison of building systems. (a) connection example; (b) exploded view of the connection; (c) bars with embedded joints.

3.2 PARAMETRIC MODEL

The parametric model logic is based on the defined hierarchy classification of the proposed system design (Figure 5). The algorithm is powered by parameters of architectural design and constructive components. For each of the component families, there are specific parameters corresponding to their types and subtypes. Architectural design parameters define the point position used to construct reference lines to positioning the components. Then these lines work as references to define the coordinates for constructing 2D elements that together form 3D components. The user controls the architecture design parameters and some component parameters (free variables), while other component parameters are automatically regulated according to architecture design parameters (dependent variables). In this generative system, all element-related parameters are dependent variables.

3.3 STRUCTURAL SIMULATION

The parametric modeling of the components allowed approaches that predicted the structural performance based on the permissible stress design. The structural analysis is executed in an application based on finite elements to where the data is exported through a plugin developed for this research. Developed in C(#) language for Grasshopper, this plugin allows that materials, profile shapes, loadings and support conditions can be defined in Rhinoceros (CAD environment). From this tool, all records are saved in a text file, following a conventional methodology in the structure analysis. Once the file is saved with the records, a program based on the Finite Element Method (CAE environment) is automatically executed, recognizing the text file as an input and proceeding to the structural analysis where internal force values and support reactions are obtained. An update of this code that allows the visualization of structural analysis results in the CAD environment is still being developed. At this stage, the automatically obtained requested forces on the bar elements feed spreadsheets where values of the internal forces and

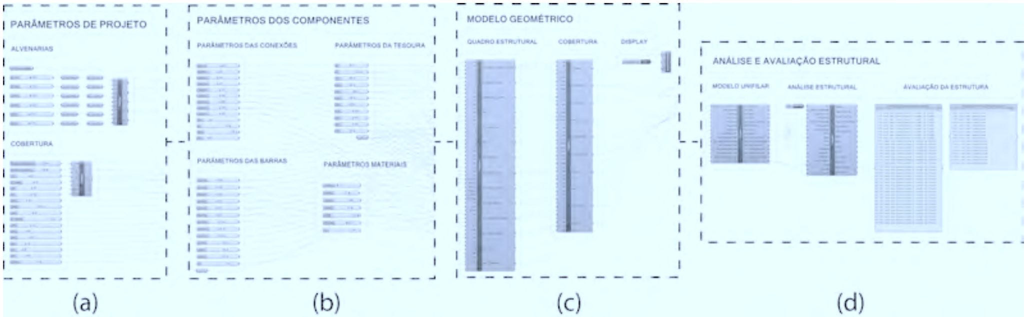

Figure 5
Building system design solutions generation algorithm. (a) architecture design parameters; (b) component parameters; (c) geometric model; (d) structural simulation and analysis.

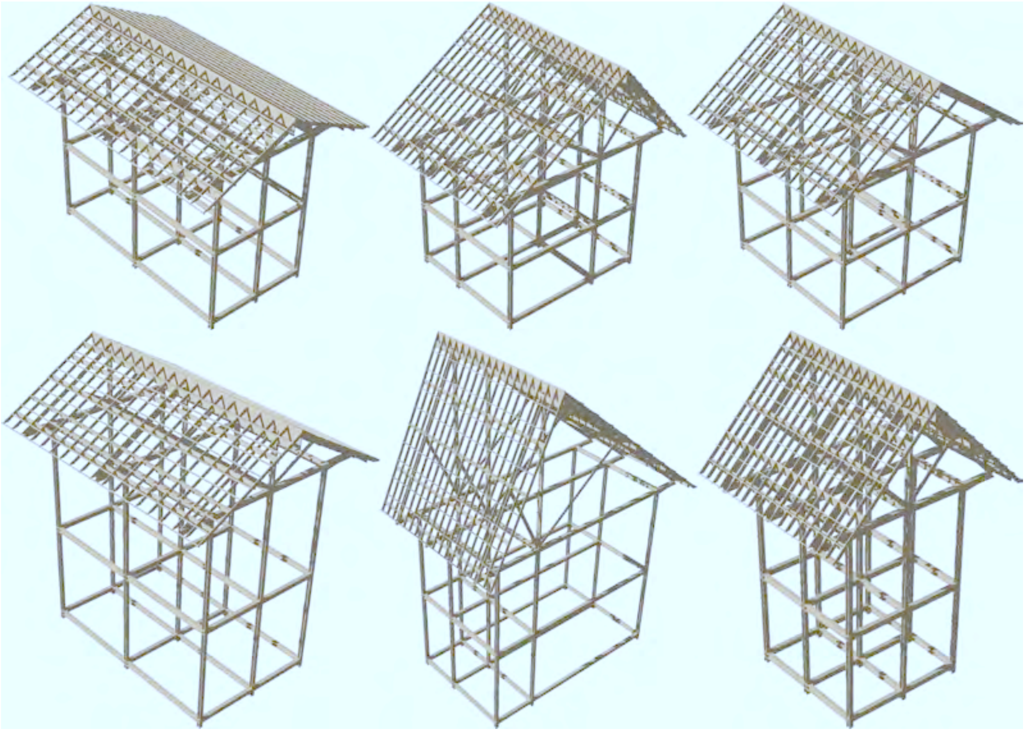

Figure 6
Design variations generated with the algorithm developed.

the necessary resistance are calculated and used to adequate the design. After the dimensions are adjusted, a message of the type "the component is well (or badly) designed" is reproduced. Since the experimental campaign for the connections' resistance estimative is still found on a preliminary stage, simplified procedures for the system's design were adopted.

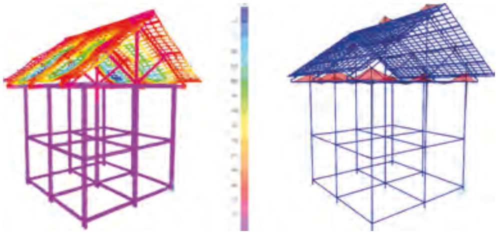

Figure 7
Structural simulation and analysis of deformation and stress in the structural system realized with the integration of CAD and CAE platforms.

3.4 PROTOTYPE

At this stage of the study, focusing on the assimilation of manufacturing techniques and evaluation of assembly aspects of connections, three samples of components were selected to be manufactured and assembled using a 1500 mm x 2000 mm x 18 mm MDF sheet. The first component was a lower connection with four exit axes (Figure 8). This component was chosen because it is an example of a relatively complex connection and because there were doubts about the integrity of the joints in some of its elements. The other two components chosen are sections of bars for beams and columns, respectively. The prototypes were fabricated on a 1:1 scale with 100mm x 100mm profile section and 18mm thickness. The elements were fabricated using a Cutlite ® CNC laser cutter machine with 1500mm x 2000mm workspace. It is important to highlight that the same pieces could as well be properly fabricated using a CNC router machine. According to the machine operators, laser cutting is more precise and is capable of manufacturing the parts in less time. However, it produces unpleasant odors on the parts and darkens the edges, producing a poor visual appearance. This becomes a problem in cases where the architecture design takes into account the appearance of the structural elements. The time needed to cut the pieces was 22 minutes.

3.5 ASSEMBLY

The assembly process of the components was based on male-female joints with 70mm depth, 18mm, and 20mm width, embedded in the elements. Two joints needed to be manually sanded for viability. The only necessary tools for the execution of the assembly were sandpaper and a rubber mallet. Also, the assembly of all three components could be made by just one person with no difficulty in less than 20 minutes. The connection between the components took less than 1 minute to be executed. The joints were connected using just pressure and, under preliminary evaluation, the integrity of connections was ensured (once two elements or two components were connected, it became difficult or impossible to separate them). How variations in the humidity of the environment affect the integrity of the connections is still under observation, but it has been noted that the joints have an higher integrity on days with higher relative humidity than on days with lower humidity.

4 CONCLUSIONS

The systematization proposed in this paper indicates the possibility of a method that allows the design of new building systems or the adaptation of existing ones that correspond local design specifications to facilitate the cultural and economic acceptance of mass customized and digitally fabricated housing. Future studies focus on how the design methodology can help to improve the definition of the variables to be considered in this systematization.

Results of this research suggest that the concepts of CAD, CAE, and CAM can be integrated to make mass customization of social housing possible through the initial development of a building system and pave the path for more detailed analysis and testing in the future.

Results on prototyping and assembly demonstrate that these processes worked. It is still necessary to verify the feasibility of sealing components.

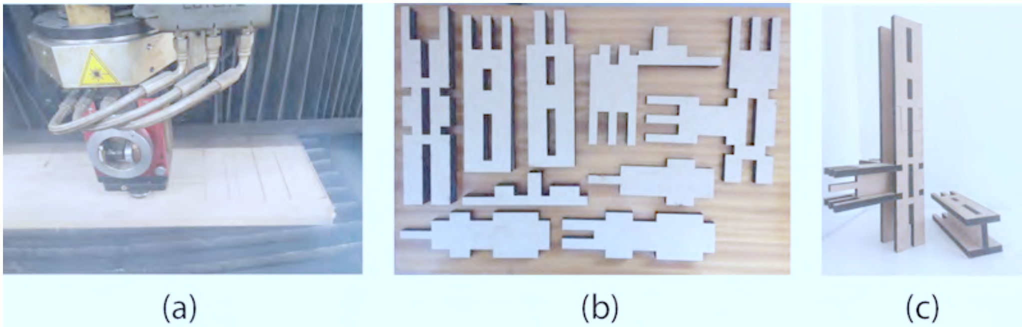

Figure 8
a) manufacturing process of the parts; b) fabricated bidimensional elements; c) assembled components.

Since the assembly process is the same as those of the tested parts, expectations are positive. The integrity of joints presents a promising scenario for the use of the designed structure in an architecture and engineering project. However, a wide range of testing and studies still need to be carried out.

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Biomimetic Reciprocal Frames

A design investigation on bird's nests and spatial structures

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Reciprocal Frame (RF) is a constructive system typically applied with timber, since it is composed by discrete elements with short dimensions. It allows the construction of large spans and complex geometries. This kind of structure has been addressed by recent research projects that aim to produce it using computational tools and digital fabrication techniques. Moreover, the enhancement of these technologies enabled the integration of simulations of biological processes into the design process as a way to obtain better and optimal results, which is known as Biomimetics. This paper describes the development of a spatial structure that combines the principles of RF and the assembly process of natural agents, such as birds, in a digital environment. The tools used for the generation of the structure were Rhinoceros, Grasshopper and different add-ons, such as Culebra, Kangaroo, Pufferfish and Weaverbird.

Keywords: *Biomimetics, Reciprocal Frame, Nexorade, Computational Design, Agent-Based System*

INTRODUCTION

Wood is one of the oldest materials used in construction, and often its first applications are confounded with the origins of architecture itself, as stated by Laugier (1755), in his primitive hut theory. Some timber constructive systems were created with the purpose of solving technical limitations, for example, the Reciprocal Frame (RF) or Nexorades (BAVEREL et al., 2000). Dated from the neolithic, it was firstly applied in primitive huts, and its application enables the construction of large spans (LARSEN, 2014; PUGNALE; SASSONE, 2014) with relatively short elements. This kind of structure has appeared in different places and cultures throughout mankind's history, e.g. a roof typology known as Mandala, in China and Japan, during the 12th century; Sebastiano Serlio's studies and Leonardo da Vinci's schemes, in the 16th century; during the early 20th century, in Pier Luigi Nervi designs and within the development of specific systems, such as Zollinger's (WINTER; RUG, 1998; TOUSSAINT, 2007; LARSEN, 2014). It is possible to notice that the use of RF has usually coincided with periods of great technological advancement, such as the one we are living nowadays, which is already being called the 4th Industrial Revolution.

Presently, with the availability of new digital technologies, many researches are exploring RF, bringing a deeper knowledge and a more scientific approach to it. One of the main interests is the possibility to achieve a higher level of formal complexity by using simple linear or planar elements with short dimensions (BAVEREL; LARSEN, 2011; PUGNALE; SASSONE, 2014; MESNIL et al., 2018). Hereby lies the sustainable approach of RF structures, since its components take better advantage of timber, reducing material waste, on top of wood being a renewable material (WINTER; RUG, 1998; GUTIERREZ; FLORES; PRECIADO, 2016).

Over the past few decades, computational design and fabrication methods have been introduced into architectural design, enabling processes that encompass the geometric differentiation of building components (KNIPPERS; SPECK, 2012) as well as the integration of material, form and structure (OXMAN; OXMAN, 2010). Commonly disregarded by traditional design and production methods (OXMAN, 2014), this integrative approach is noted in the hierarchically structured world of natural organisms (WEGST et al., 2014), which enables the direct exchange of information between the scientific fields of Architectural Design and Biology (AHLQUIST et al., 2015). Resorting to Nature has been a recurrent topic in the history of Architecture (BAHAMÓN; PÉREZ; CAMPELLO, 2008; STEADMAN, 2008). In a first moment, Nature was taken as a source of inspiration for visual representation. Gradually, Nature was also used as a philosophical analogy. With a deeper understanding of natural processes, it has been possible to develop artifacts based on natural mechanisms; recent computational advances in design, simulation and fabrication allow biological processes and natural phenomena to be comprehended as methodological strategies to achieve technical solutions (KNIPPERS; SPECK; NICKEL, 2016). This approach is commonly named Biomimetics.

Given the importance of sustainable design approaches to economic and ecologic criteria in view of the worldwide concern on climate change and energy resources, this paper examines if architectural design could undertake Nature's strategies into a RF design process in order to emulate the structural and material performance of complex structures found in Nature. In this sense, the objective of this paper is to develop a digital spatial structure with discrete irregular elements, such as a pavilion, based on both RF principles and accounting assembly strategies performed by natural agents, such as birds.

BEHAVIORAL BASIS

As stated by Gherardini and Leali (2017), the guidelines established by Biomimetics are known as ways of perceiving environmental, economical and/or structural efficiency and functionality. Although emulating natural processes does not necessarily result in aesthetic value, Allen and Zalewski (2009) suggest that there is a human fascination in natural principles of form, such as in the idea of "ordered disorder" and "natural growth". This means that an aesthetical value might be attained by exploring the intrinsic relationship between natural structures and their mathematical principles. In this sense, RFs mathematical principles, such as mutual equilibrium, can be found from basic geometry until complex biological structures (PIZZIGONI, 2009). Exploring these principles encompassing material properties, construction logics and integration of design, fabrication and assembly might be a way to obtain optimal results and innovative solutions. Therefore, in order to develop the design of a spatial structure of this kind, it was necessary to understand the behavioral basis of both birds' nests assembly process and the RF essential mechanisms.

Agent-Based Systems

Through the emulation of natural phenomena and biological behavior it is possible to achieve some level of integration between form, process and ecosystem, providing optimal solutions under certain restrictions (BENYUS, 1997). In nature, living organisms may be considered as systems that achieve their degrees of systemic complexity through the interaction of external pressures of the environment and their own internal components. Their maintenance is done by adaptive evolution and by shifting specific behaviors (PEDERSEN ZARI, 2007; MENGES; WEINSTOCK; HENSEL, 2010). Thus, biomimetic approach requests an integrated design methodology that encompasses material properties, development tools, fabrication equipment and an environment that provides active inputs into a bottom-up process. These inputs enable an adaptive behavior that perceives the optimal self-organization of the organism, which is a way of exploring emergent and unexpected complexities. A computational data processing method capable of translating and integrating these demands is the *Agent-based System* (BAHARLOU; MENGES, 2013; BAHARLOU; MENGES, 2015). Based on the behavioral pattern of natural agents, it consists of a collection of autonomous decision-making digital entities that follow simple local rules that trigger the interaction with the environment (GILBERT, 2008).

The behavior of every agent arises from a starting set of rules that defines certain strategies in response to recurring new situations and guides the decision-making processes (HOLLAND, 1995). This basic set of rules can be modified by agents along the process by acquiring environmental information over time and, hence, generating new sets of rules and promoting dynamic adaptations (BAHARLOU; MENGES, 2015; CASTI, 1997; BAHARLOU, 2017). Furthermore, unexpected and new events may emerge from individual or collective behavior of agents. When an agent is involved in the process of form generation, it is considered as an individual being, such as a bird building its own nest (BONABEAU, 1997).

The bird nest can be considered one of the best examples of RFs in Nature, since their structural and mathematical principles are the same of artificial RFs. It is remarkable that both are made from simple discrete elements and create a narrative and aesthetic expression, as stated by Song et al. (2013). Nevertheless, while artificial RFs present a highly symmetric pattern and similar fans, natural RFs are made from completely irregular, non-symmetric and inaccurate elements.

Reciprocal Frame: Structure and Elements

RF are also known as Nexorades, which implies in the term nexor, referring to the individual elements that constitutes this kind of structures (BAVEREL et al., 2000; PUGNALE; SASSONE, 2014). Larsen (2014) points out that each nexor is characterized as short linear or planar element, that integrates closed and complex systems. RF essential concept relies in the relationship between supporting and being supported simultaneously and symmetrically. These functions do not constitute a structural hierarchy and a single connection point of a nexor cannot overlap the same function. Moreover, each nexor has always four different connection points (two supporting and two supported), located along the element. The region established by the encounter of nexors is called fan and it is considered as the elementary geometric pattern of these structures. At least three nexors are necessary to constitute a fan. More recently, Araullo (2018) has suggested the term "DNA" as a biological analogy. The spatial configuration generated by the fans implies in overlapping of nexors eccentricity, which refers to the smallest distance between the axis of two connected elements (BAVEREL et al., 2000, DOUTHE; BAVEREL 2009, SÉNÉCHAL; DOUTHE; BAVEREL, 2011 , THONNISSEN, 2014, MESNIL et al., 2018).

In regards to structural aspects, RF main effort demands are from axial and flexion loads, and due to its very complex behavior, Finite Element Analysis techniques are the most common strategy adopted to obtain the best structural configurations. Mesnil et al. (2018) have demonstrated that this type of structure has very peculiar properties, which should not be treated through conventional techniques. Brocato (2011) suggests that the optimal configuration of RF may be found by reducing the axial forces and increasing the bending, which is the opposite of what is usually done in shells or gridshells. On the other hand, Kohlhammer and Kotniki (2014) point out that, by analyzing each nexor, their individual behavior is very close to traditional beams.

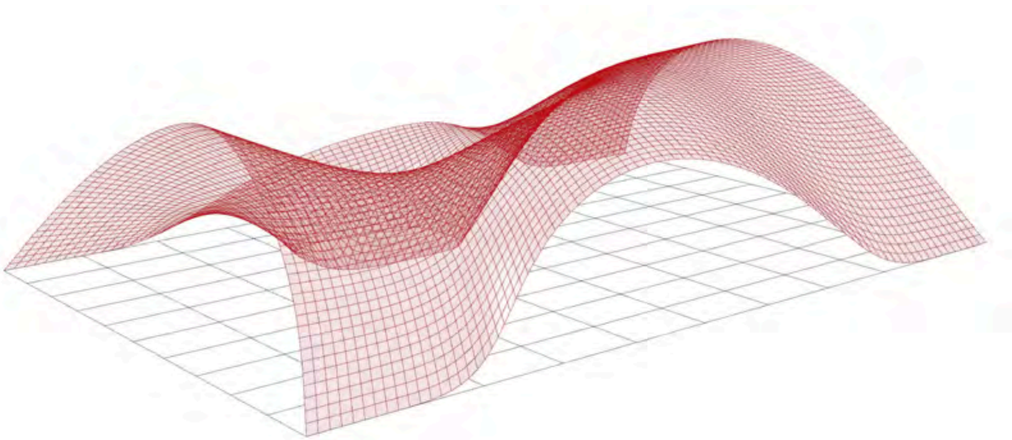

Figure 1
Generated geometry of the Pavilion, using Form-Finding Techniques. Font: Authors, 2019

INTO THE ALGORITHM

The design process was developed using Grasshopper algorithmic modelling tool for Rhinoceros 3D, with specific add-ons for the emulation and analysis of the design. The process consisted in three different stages: (1) initial setting, (2) *Agent-Based System* simulation, and (3) RF setting. The first step consisted of defining a rectangular mesh (30x20m) with an internal cutout of 1/5 of the total area (6x4m). Considering the four boundary points of the mesh, as well as the internal rectangle as supports, the global shape for the pavilion was generated with form-finding techniques with Kangaroo Physics add-on (Figure 1).

Decoding Nature

In the second design stage, the process of a bird's nest assembly was translated into a design construction algorithm that emulates the building behavior of such natural agent. In order to achieve that, it was necessary to set the *Agent-Based System* with the aid of Culebra 2.0 add-on, which enables dynamic interactions between multiple agents in hybrid systems within a behavior library, computing data in two or three dimensions. Besides the geometry from the previous step, there are three main settings that must be defined in order to start the simulation: (1) agent set, (2) behavior set and (3) visual resources.

The bird's nest assembly process started with a single wood stick. It is a three-dimensional structure without a precisely geometric boundary, so the initial settings of the agents were matched with these criteria. Also, the agents' movement adjustment defines maximum and minimum dimensions and angles of each stick, which are very irregular in the whole natural structure. The initial settings for the simulation were defined as: Spawn Settings: 1, Dimensions: 3D, Bounds: None; and for movement configuration: Initial Speed: 1.0 m in axis Z, Maximum Speed: 3.0 m/s, Maximum Force: 0.3 m/s^2, Velocity Multiplier: 1.5 units.

The assembly process of a bird's nest has some level of linearity, since the order is set by the first stick in connection to the next one, then in a loop. However, there is an unexpected randomness generated by the dynamic interaction of the elements. When a bird's nest is analysed, the inner and outer boundary are irregular because of the dimensional tolerances of each stick. Moreover, at times these sticks might be much larger or smaller than expected (Figure 2). These characteristics should be translated into the al-

Figure 2
Agent-Based System trail and cloud points representation in Rhinoceros and Grasshopper. Font: Authors, 2019.

Figure 3
Fallen bird's nest. Some of the sticks go much farther than the whole structure boundary. Font: <https://commons.wikimedia.org /wiki/ File:Nedfalt_-fuglerede.JPG>. Accessed in: 14/05/2019.

gorithm through the Behavioral Settings. First, the tracking behavior should incorporate the desired geometry and its expected dimensional tolerance, such as the outer projection distance. At the same time, the wandering behavior should simulate direction and dimensional unexpected randomness, showing that it is possible to have a certain level of order and control. The tracking behaviors were defined as the Pavilion Form-Found Geometry, Another Agents Detection Limits: 1.5m, Projection Distance: 2.5m and Radius Projection Distance (Multiplier): 1.45 m; and for wandering behavior: Randomness Control: 100 units, Wander Radius: 15.0 m, Wander Distance: 15.0 m, Rotation Trigger: 6.0 m.

At last, it was necessary to calibrate the visual representation of the simulated system, enabling a graphical output, such as a sequence of lines connecting a point cloud, which should be the final geometry of the *Agent-Based System*. After more than 700 iterations, the output of this stage was the simulated bird's nest trail based on a cloud of more than 700 points (figure 3).

Reciprocal Frame Conversion

Since many of these points were too close or too far from each other and it would not be possible to ensure every element's connection in four vertices, it was necessary to reduce the total number, considering the proximity between them, defined as a minimum of 0.5m. At the same time, it was imperative to embed some restrictions to the behavior of natural agents into actual RF segments, and one of them was the definition of fans made by four different nexors. Although this might not be the best structural option, it is the most precise configuration to assure the number of connection points, due to its grid similarity. With every point defined, they were splitted between UV coordinates according to the pavilion shape, and were connected by lines. With the help of add-ons such as Weaverbird and Pufferfish, some of the geometric relations were improved, reducing distortions of fans and establishing a defined boundary for the most external nexors.

An algorithm capable to adapt RF into different surfaces, currently under development as a PhD research by one of the authors, was applied in order to transform the UV lines into RF elements. Basically this is possible through a set of geometrical and mathematical operations, such as rotating the lines in a certain angle, projecting the points into the intersection planes, connecting points in different heights (in order to guarantee the RF support logic and control the eccentricity), extending the extremities and defining the section dimensions. Since the structure was designed to be constructed with rods, the eccentricity and section dimension was almost the same (0.03 m), the extension of nexors was 0.07 m and the rotation angle in the center of each line of 7 degrees. The generated structure had a total of 820 nexors, with lengths ranging from 0.49m to 3.5m and around 200 totally different fan geometries (figure 4).

RESULTS

By one hand, this experience glimpses the potential by integrating the natural processes of assembly, such as birds nests, with the already known restrictions and demands of RF made by men. The use of biomimetic principles into the design methodology may ensure much more interesting formal solutions, and it might also provide a more efficient, structural and economical solution. The resulting structure for the pavilion has a high level of morphological complexity and variety. Each connection angle and geometry, nexor dimension and fan configuration is unique, which can only be produced using digital fabrication technologies.

By the other hand, one of the main issues is the connection system between all nexors. It is possible to design and even fabricate elements using simple dovetail or bridle joint systems, but the assembly process would be hard or even impossible, due to the relation support-supported and the global geometry. Actually, the connection system is considered an issue in multiple RF situations by many authors. As stated by Araullo and Haeusler (2017), the connection point in linear and in planar nexors implies in peculiarities that cannot be solved by using off-the-shelf standardized products. Nevertheless, the final structural condition of the structure was not verified,

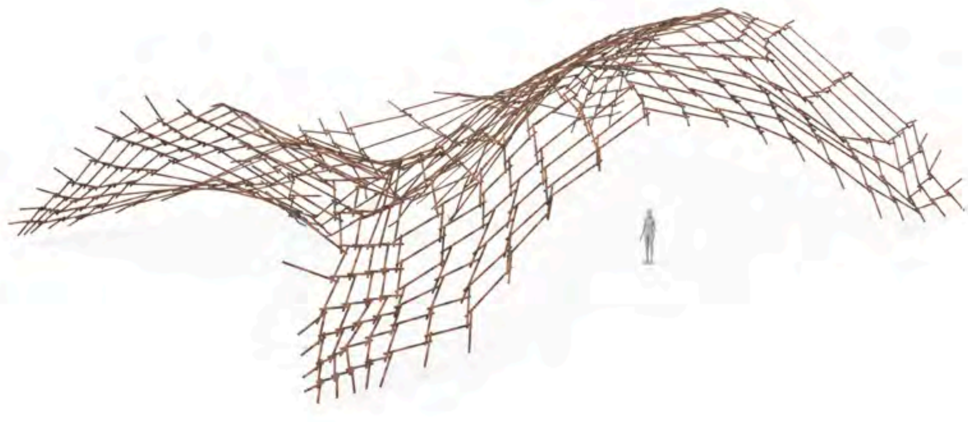

Figure 4
Reciprocal Frame Structure generated using the grasshopper alogirthm. Font: Authors, 2019.

nor the strategies that should be used to settle it.

Finally, the digital data generated from the simulated bird's nest structure and the one from the RF configuration look very similar, as it can be seen in Figures 3 and 4. However, the RF structure was generated considering only UV coordinates, while the simulated nest presented also used the W coordinate. In another words, the RF algorithm works undertaking any kind of surface, without thickness, but nature works with material-based elements. We expect this experience may encourage more research projects integrating RF theories and concepts with Bio-inspired methodologies, looking into other natural structures.

FUTURE WORKS

The discrete elements will be structurally optimized with the integrated use of structural analysis add-on Karamba3D for Grasshopper and built-in evolutionary solver component Galapagos, in order to assure the minimum displacement of the whole system.

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Architectural Design in Open-Source Software

Developing MeasureIt-ARCH, an Open Source tool to create Dimensioned and Annotated Architectural drawings within the Blender 3D creation suite.

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MeasureIt-ARCH is A GNU GPL licensed, dimension, annotation, and drawing tool for use in the open source software Blender. By providing free and open tools for the reading and editing of architectural drawings, MeasurIt-ARCH allows works of architecture to be shared, read, and modified by anyone. The digitization of architectural practice over the last 3 decades has brought with it a new set of inter-disciplinary discourses for the profession. An attempt to utilise `Open-Source' methodologies, co-opted from the world of software development, in order to make high quality design more affordable, participatory and responsible has emerged. The most prominent of these discussions are embodied in Carlo Raitti and Mathew Claudel's manifesto `Open-Source Architecture' (Ratti 2015) and affordable housing initiatives like the Wikihouse project (Parvin 2016). MeasurIt-ARCH aims to be the first step towards creating a completely Open-Source design pipeline, by augmenting Blender to a level where it can be used produce small scale architectural works without the need for any proprietary software, serving as an exploratory critique on the user experience and implementations of industry standard dimensioning tools that exist on the market today.

Keywords: *Blender, Open-Source, Computer Aided Design , OSArc*

OPEN SOURCE AND OPEN SOURCE ARCHITECTURE

In our current technological era a new architectural discourse has sprung up in an attempt to breath new life into the ideals of Participatory Architecture championed by the likes of Christopher Alexander, Giancarlo DeCarlo and Cedric Price in the mid 1900's. Re-Branded as "Open-Source" (a term co-opted from software developers) the Open-Source Architecture (OSArc) movement defines itself as "an emerging paradigm[...] drawing from references as diverse as open-source culture, avant-garde architectural theory, science fiction, language theory, and others, it describes an inclusive approach to spatial design the **collaborative use of design software**, and the transparent operation throughout the course of a buidings [...] life cycle". (Ratti 2015) While this description leaves room for a lot of interpretations, the flavour of OSArc that this work seeks to promote is one that is able to be freely shared and accessible to as many people as possible.

To understand the lofty ideals of the OSArc movement it is useful to understand the origins of the Open-Source software movement whose terminology the OSArc movement has co-opted.

Open Source Software
The beginnings of the Open Source movement can largely be attributed to the work of Linus Torvalds and his work on the Linux operating system kernel, which he released for free in 1991. This would spark other developers to begin releasing their source code for free, most notably Netscape would release their web browser (now known as Mozilla Firefox) and its source code to the public in 1998 and coin the term "Open-Source". Importantly this was accompanied by 'Copyleft' licences like GNU GPL that are a manipulation of traditional copyright law to ensure that any derivatives of open-source code must also be released as open-source under the same license, a protection that these works would not have if they were to be released into the public domain.

OSArc
Carlo Ratti and Mathew Claudel's manifesto "Open Source architecture" began life as collaborative Wikipedia page in 2011 that would serve as the kernel for an article published in domus that June. (Ratti 2011) After the article's publication, the text continued to grow into the book that was eventually published in 2015. Ratti and Claudel (and a host of many other collaborative authors) propose that the next evolution of participatory design is one that will build on the success of the open source software movement by creating an 'open-source' Architecture. An architecture that can be shared modified and redistributed but will ultimately be composed by what they refer to as the "Choral Architect" who weaves together these disparate ideas of the populous into a harmonious whole.(Ratti 2015) The text itself and its successful collaborative authorship would seem to be a positive indicator of the potential of this mode of working. However the translation from Open-Source text to 'Open-Source' Architecture is quite challenging.

The Nature of 'Sources'
Open-Source Software relies on the fact that Software can be collaboratively shared modified and reproduced solely from its source code. In basic terms a software's source code is plain text written in a human readable programming language that can be compiled to produce the computer readable machine code that is the software. It's important to note here that, because a software's source code is simple plain text, anyone with access to a computer and the internet can obtain, modify, and compile the code to a usable program without the need for any commercial tools. This means that the barrier to entry for an open source project is incredibly low. Unfortunately this is not the case with OSArc (Vardouli 2012).

Most OSArc projects treat the virtual representations of a building (its 3D models, BIM Data, CAD drawings etc.) as the 'Source-Code' of architecture, and utilize common Open-Source platforms like GitHub to share and manage the collaborative editing of this data. However, unlike software source code which is comprised of plain text, this Architectural data requires the use of specialized commercial software to read and edit. OSArc projects have excelled at the sharing of their Architectural data over the web, however the industry standard tools available for editing it are commercial, closed-source, and proprietary which imposes a serious barrier to entry. The cost of these industry standard tools poses a substantial problem for OSArc, as the success and longevity of Open Source Projects is typically directly correlated to the size of the community it can engage in development. For this reason, this work argues that for an OSArc project to be successful (and Open-Source, in the truest sense of the term) then the set of tools necessary to interact with the Architectural data of that project must be open-source as well.

WikiHouse

Wikihouse, an 'Open-Source' architectural project founded by Alastair Parvin and Nick Lerodiaconou in 2011 is a contemporary attempt to leverage the design talents of the masses to produce an innovative system for affordable housing. Their unique structural system WREN v4.3 consists of an assembly of pieces that can be cut from standard plywood sheets on a CNC Machine. All of the plans are released for free on the organizations GitHub and are licensed MPL2.0 meaning collaborators are free to download and modify them as they see fit.

Wikihouse has seen a good deal of media coverage, with several built projects, and general praise for their advancement local digital manufacturing and low income housing and construction. However, The WREN structural system as it exists on GitHub, throughout its 58 revisions, has only 2 contributors both members of the Wikihouse foundation. The smaller Microhouse system fares slightly better, with 3 contributors. The 'source code' that they've shared for the WREN system is based in Rhino's Grasshopper, this means a minimum buy in of $995 for an individual to engage with the project, and McNeils Rhino is on the cheaper end when it comes to architectural software. To an established architecture firm $995 may seem like a nearly insignificant cost, but it's important to remember that the lifeblood of an Open-Source project is individual, volunteer participation, which means that for a project to grow and flourish the barrier to entry must be as low as possible, and this is a difficult problem to overcome when looking at the landscape of architectural software available today.

BLENDER AND MEASUREIT-ARCH

Our tool, MeasurIt-ARCH aims to provide an Open-Source alternative that OSArc projects can utilize to ensure that their barrier to entry is as low as possible. It is a dimensioning and drawing plug in, based on the MeasureIt tool created by Antonio Vazquez, developed for Blender, the Open-Source 3D creation suite started by Ton Roosendaal in 1995.

Blender

Blender started life as a proprietary tool for NeoGeo a Dutch animation studio co-founded by Roosendaal. From 1998 - 2002 Blender continued to be developed by Roosendaal under the company Not a Number. In 2002, following Not a Numbers shutdown, the community surrounding blender, initiated by Roosendaal, raised 100,000 Euros to purchase Blenders licensing from the Not a Number investors and re-release it as an Open-Source software under the GNU GPL license [@foundation]. Since 2002 Blender has seen stable development and a robust community.While Blender has been developed with a predominant focus on animation, there are several aspects of Blenders design that make it uniquely suited to be used as an architectural design tool;

1. **Realtime PBR(Physically Based Rendering)**. Blenders latest release features the EEVEE rendering engine. Which can simulate photorealistic, lighting and material characteristic (including reflection and refraction), while you work. This is a similar feature set to Lumion, a rendering tool frequently used in conjunction with SketchUp or Revit.
2. **Procedural Modeling**, more commonly referred to as parametric modeling in the Architectural industry, generates forms based on a series of rules and input parameters. In Blender this is accomplished through the modifiers system. Which takes a simple input mesh parameters and preforms operations to it to generate or deform it into something new. Blenders driver system allows the user to derive input parameters from virtually any property of any object in the scene. Jacques Lucke is currently in the process of developing this modifier system into a node based interface, similar to Rhino's Grasshopper, and node based Parametric modeling is already possible in Blender through the use of either the animation-nodes addon (also created by Lucke) and the Sverchok addon.
3. **Object MetaData**.While it is beyond the

scope of this work to add BIM functionality to Blender, it is important to note that Blenders data structures and code infrastructure are already well situated to handle adaptations to manage the kinds of object metadata required to facilitate a BIM workflow. Users can already define custom properties that are attached to an object and use these custom properties in conjunction with the Driver system to make them influence geometry. Objects can also be linked across blender files, meaning that a user can create collections of objects with customizable parameters that can then be linked into the current working file, in a workflow similar to Revit's Families, or SketchUp's Components. The user interface to preform these tasks is not particularly intuitive at the moment, however the basic functionality to carry out BIM-like tasks exists and could be improved in the future.

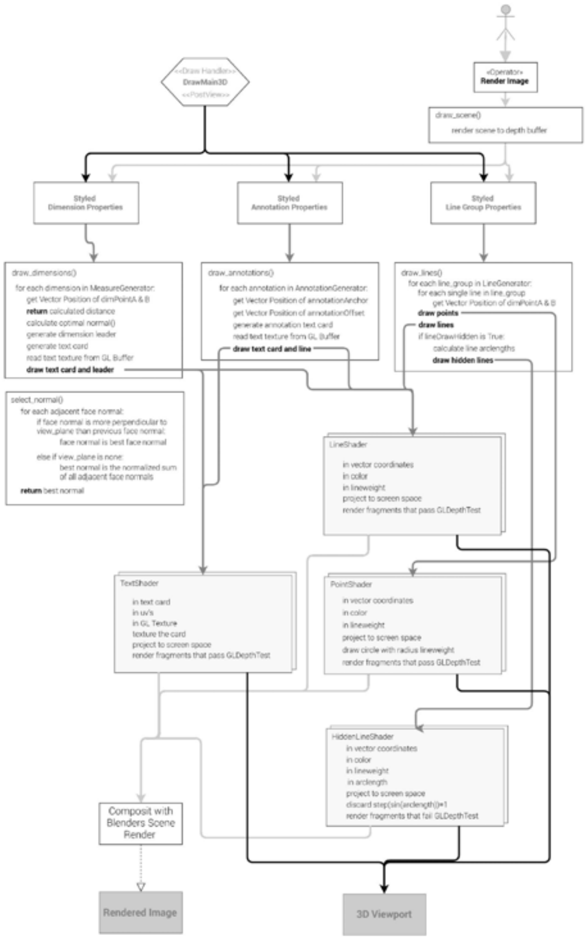
Missing Dimensions
That being said, Blender lacks any ability to produce working drawings. This is a major detriment to its possible adoption by the architectural industry or use in OSArc projects. MeasureIt, an addon produced by Antonio Vazquez, added basic dimensioning tools to blender, but the addon has no support for Dimension Styles, or Line drawing, both features necessary to produce architectural drawings in an efficent manner. MeasureIt-ARCH, the tool developed in this work, builds on Vazquez's addon to add in this missing functionality, and optimize the user interface and tools for use cases typical to architectural practice.

MEASUREIT-ARCH, FEATURES AND DESIGN PRINCIPLES
Creating an Open-Source set of dimensioning annotation and linework tools means writing them from the ground up. This provides an opportunity to rethink the paradigms and systems that define these tools and how they are implemented in industry standard software packages, and try and do better. Each of MeasureIt-ARCH tools, while inherently pragmatic in nature, try to take a critical stance in their implementation, subverting in subtle ways the expected modes of operation of dimensioning, annotation, and linework tools. At the core of each of these alterations is the driving principle behind MeasureIt-ARCHs design, avoid enforcing reductions to 2 Dimensional planes, embrace and engage the inherent complexity and opportunity of 3 Dimensional space, and make use of its depth and context whenever possible.

Figure 1
MeasureIt-ARCH Data Structures Diagram

A Hybrid System
For MeasureIt-ARCH to be a real time, 3D dimension system it needed to fully integrate with Blenders 3D viewport systems. MeasureIt-ARCH is able to do this by utilizing Blenders robust Application Programming Interface (API). Application Programming Interfaces are a relatively common feature of large software applications, they provide users the ability to access certain aspects of the software through a programming language. Revit, Rhino, and SketchUp all feature API, however their depth and usefulness vary. Typically the scope of an API allows users to write addons for the automation of repetative tasks,

Figure 2
MeasureIt-ARCH
Draw Code Diagram



and the importing and exporting various filetypes. Chaining together the existing toolset of a software can be substantially powerful, Rhino's Grasshopper plug-in is a prime example of this, however Blender's API takes things a step further, providing low level access to some of the software's core functionality. This is essential for MeasureIt-ARCH as it allows the addon to create brand new tools and elements that integrate directly with the parts of the software that draw the 3D environment to the screen.

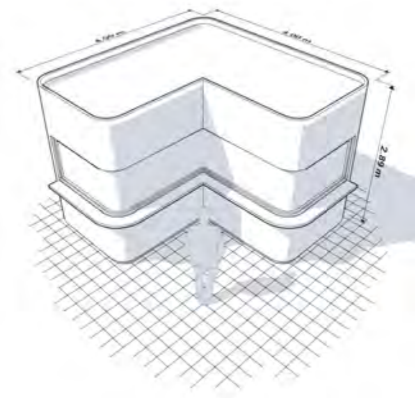


Figure 3
MeasureIt-ARCH Elements over a grey scale render

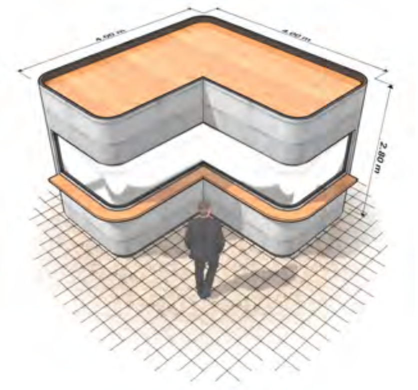


Figure 4
MeasureIt-ARCH Elements over a Real Time PBR Render

Blenders drawing system can utilize 3 distinct render Engines. Eevee, A realtime engine comparable to the rendering capabilities of software like Lumion, or Unreal-Engine, Cycles, a raytracing renderer comparable to renderers like v-ray or maxwell, and the Workbench engine, a simple and fast engine to draw the working viewport. While the Workbench engine is the predominant viewport render engine, any of the 3 engines can be used in real time while working on a model.

Overtop of the main render engine (either Eevee, Cycles, or Workbench, depending on which the user currently has enabled). Blenders Overlay system draws other elements necessary for interacting with the 3D environment. MeasureIt-ARCH functions in the same way as the Overlay system. This means MeasureIt-ARCH elements can be layered over any of Blenders render engines for a variety of visual styles. Even through MeasureIt-ARCH is an Overlay, in the sense of the render pipeline, it still accesses the same 3D information as the main Engine allowing its elements have the appropriate depth ordering.

This Hybrid system allows MeasureIt-ARCH to take full advantage of Blenders rendering capabilities, and can blur the distinction between rendered image, and dimensioned drawing, if desired.

Automated Placement of dimensions

Current Industry tools like Autodesk's Revit and McNeels Rhino deal with dimensions only in the 2D plane. The creation of Dimensions in these packages requires the user first to specify a "Work Plane" (or CPlane in Rhino) onto which dimensions will be projected. This approach one key advantage, as the number, and complexity of computations required to properly locate and display the dimension element in 2D are significantly reduced. Dimensions projected on a 2D work plane then can be quite efficient when the desired end product is a 2D plan, section, or elevation drawing of predominantly orthogonal geometry. However 2D work-plane dependant dimensions begin to cause issues in efficiency when working with 3D isometric or axonometric views, as the work-plane needs to be manually redefined by the user to add dimensions to each axis. Things become especially problematic when dealing with non-orthogonal geometries any complex geometric form requires multiple unique work-planes to be thoroughly dimensioned, and any modifications that move the geometry off of the dimensions work-plane will result in the models connection to the dimension to break and be deleted (as is the case with Revit), or become useless nonsense (as is the case with SketchUp). 2D dimensioning workflows present other limitations as well, such as Revits inability to display dimension elements in perspective views. This layer of abstraction for the sake of computational simplicity impacts the usability and efficiency of these dimensioning tools. Can we remove the work plane and it's limitations, what new possibilities does this allow, and what new challenges does it present.

Firstly lets examine how the computations required to a dimension change when moving from 2D to 3D. Adding a dimension in 2D is fairly trivial. We need to draw some extension lines perpendicular to the points we're measuring, and a dimension line with some text parallel to the points we're measuring but offset by some amount. The bulk of the computational work here is involved in finding the correct perpendicular direction. For a 2D line A defined by values (x,y) its two perpendicular lines would be (y,-x) (a 90 degree rotation counter clockwise) or (-y,x) (a 90 degree rotation clockwise). With only two options to choose from a piece of software can very simply rely on sampling the users mouse movement to decide which of options to choose, and how long to make the perpendicular extension lines.

Moving up to 3D things become more challenging, while in 2D space there were only 2 possible perpendicular lines to choose from, in 3D space there are an infinite set of perpendicular lines. Trying to choose the users intended option from this infinite set using only mouse input would be unreliable and frustrating for the user. This leaves us with 2 options, maintain the status quo and reduce the problem back to 2D space by having the use pre-define a work-plane, or utilize more information from the 3D environment to select the correct perpendicular direction without any user intervention.

To select the correct perpendicular direction without any user intervention we first need to develop a series of rules defining how dimensions should ideally be placed:

1. Dimensions should never be placed inside of an object
2. Dimensions should remain perpendicular to one their adjacent faces.
3. Dimensions should be as close to parallel as possible to the desired viewpoint to ensure readability.

Implementing these rules requires information about the geometry surrounding the dimension and the desired view direction

Using this information, and some linear algebra its possible to produce an algorithm that properly places the dimensions without manual user input. The resulting algorithm, as it is currently implemented in MeasureIt-ARCH can place Dimension elements in a useful and predictable manner on orthogonal and non-orthogonal geometries, and automatically adjust its location as the geometry is modified. Also, because the correct placement relies only on the 3D context and not user defined inputs, multiple dimensions can be added simultaneously through a single use of the dimension tool, a feature that, even if possible, has never been implemented in a work-plane based dimension system.

The downside to this method, as mentioned earlier, is that it significantly more computationally intensive. It requires querying nearby geometry, a series of matrix multiplications, as well as several conditional checks to ensure the algorithm functions as expected even in special cases when some of the expected information is not available to it. That being said modern computer systems have more then enough capacity to deal with this added complexity. To put this in perspective, adding 32 dimension elements with the dimension tool in MeasureIt-ARCH takes just under 3 seconds, a little less that 0.1 second per dimension. While this is relatively slow operation in computational terms, it seems like a reasonable trade-off when compared to the user input time required to add each dimension individually in conventional software packages.

Realtime Dynamic Linework

MeasureIt-ARCH lines are aware of their context in the 3D scene, allowing them to automatically change how they are displayed(based on the user defined line style), if they are hidden by other geometry, or if they represent the silhouette of an object. This means that easily readable line drawings and diagrams can be produced without the need for the Architect to manually define each individual lines properties.

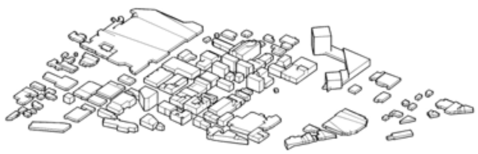


Figure 5
MeasureIt-ARCH Dynamic Linework on a city massing model (approx. 5,000 Edges). Runs in real time at 30 frames per second

MetaData Based annotations

MeasureIt-ARCH adds an annotation system the utilizes Blenders custom object metadata. This means that objects can be quickly given identifier tags, manufacturer information, or any other useful metadata, and this information can be used to populate drawing annotations. A toolset to collect and output schedules from this metadata is planed to be completed in the coming months, but is not yet implemented.

Style System

Lines, Annotations, and Dimensions can all utilize common Styles. Styles can be picked an assigned during the elements creation. The style system, like any CAD style system make it easy to maintain consistency across drawings.

SOFTWARE TESTING

In addition to the development of MeasureIt-ARCH, this work also involves the testing of Blenders abilities in real world design scenarios. Ongoing work for the Lodge at Pine Cove serves as a real world testing ground not only for MeasureIt-ARCH but for Blenders overall capacity to be utilized in architectural projects. Working for a real client ensures that the software holds up, not only in a theoretical sense, but is usable even under time pressure and realistic deadlines and time budgets. Developing the MeasureIt-ARCH in a cycle of software improvement and design implementation helps ensure that the changes made are practical in their intended use case.

This testing has motivated improvements in line quality and and the organization and implementation of the style system in order to improve the efficiency of the working process. It has also exposed vulnerabilities in the text orientation system, which will be the focus of development for the upcoming months.

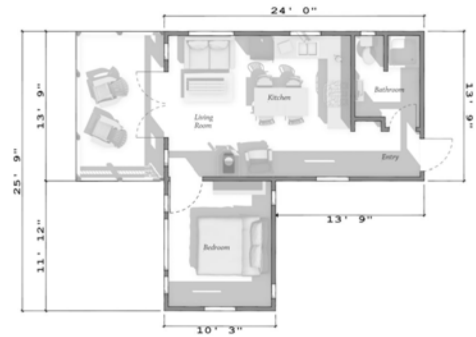
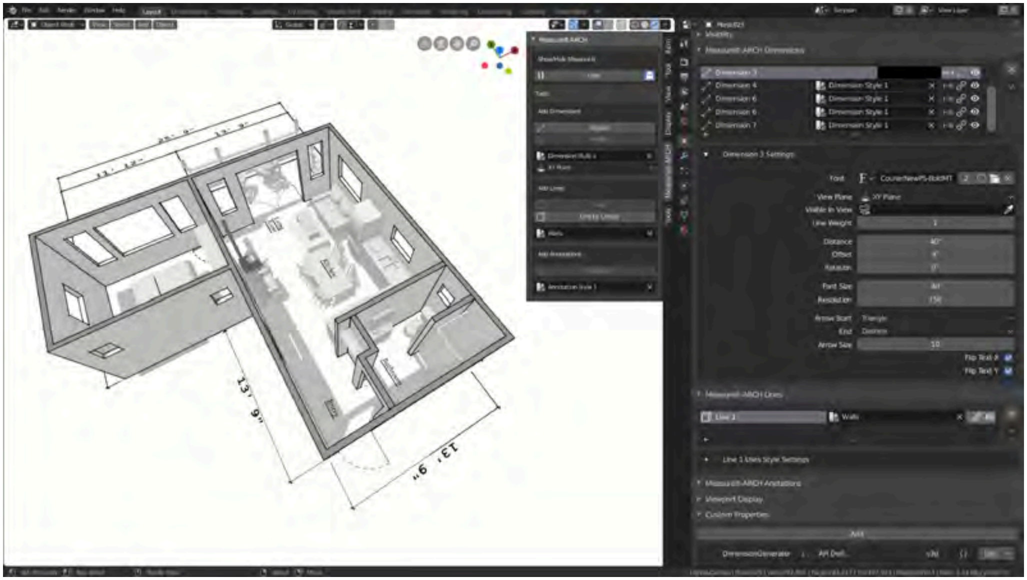


Figure 6
MeasureIt-ARCH Plan produced for the Lodge at Pine Cove

COMMUNITY ENGAGEMENT

For MeasureIt-ARCH to survive and grow it needs to engage with both the Blender community, and the Architectural community using methodologies that are appropriate for each of the respective groups.

Figure 7
A Screenshot of the MeasureIt-ARCH UI while working on a plan Produced for the Lodge at Pine Cove



For an Open-Source project to survive, there is nothing more important than its community. Rather than solely relying on traditional academic modes of information collection and dissemination, this project aims to truly embrace a the Bazaar style of open source Methodology described by Eric S. Raymond (Raymond 1999), sharing the work through modern media outlets into the communities it seeks to engage with as often as possible, to generate direct feedback about the ideas proposed, and promote discussion. For engaging with the Blender community MeasureIt-ARCH has been utilizing GitHub, to keep the management of the project as open and transparent as possible, and to provide a place where those interested in testing and providing feedback on the project can access it at any stage in its development . To share the project throughout the community and direct those interested to the GitHub page, tutorials on the use of the tool, and time lapses of it in action on demonstration projects are being recorded, published on YouTube and shared through blender community. The first round of community engagement, published on March 24th, has resulted in some reasonably substantial feedback which has lead to major bug fixes in the MeasureIt-ARCH software, including resolving, compatibility issues with the MacOSx operating system, save and load issues breaking the text drawing system, and line drawing issues caused by differences in OpenGL support across graphics hardware.

In addition to bug fixes, community engagement has resulted in the creation of a public project planning board on the GitHub platform to manage and prioritize community feature suggestions, as well as my own development plans for the MeasureIt-ARCH tool. The MeasureIt-ARCH GitHub can be found at (https://github.com/kevancress/MeasureIt-ARCH)

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Interaction - HUMAN-COMPUTER

Making use of Point Cloud for Generating Subtractive Solar Envelopes

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As a contextual and passive design strategy, solar envelopes play a great role in determining building mass based on desirable sun access during the predefined period. With the rapid evolution of digital tools, the design method of solar envelopes varies in different computational platforms. However, current approaches still lack in covering the detailed complex geometry and relevant information of the surrounding context. This, consequently, affects missing information during contextual analysis and simulation of solar envelopes. This study proposes a subtractive method of solar envelopes by considering the geometrical attribute contained in the point cloud of TLS (terrestrial laser scanner) dataset. Integration of point cloud into the workflow of solar envelopes not only increases the robustness of final geometry of existing solar envelopes but also enhances awareness of architects during contextual analysis due to consideration of surface properties of the existing environment.

Keywords: *point cloud data, solar envelopes, subtractive method, solar access*

INTRODUCTION

Awareness to consider solar access during the development of built environment principally is taken into account since the Ancient period. This can be observed through several examples such as The Hanging Gardens during the Babylonian period in 605-562 BCE (Cartwright 2018), El-Lahun village in Egypt (1857-1700 BC) with a checkerboard urban grid and narrow streets facing North-South (Mazzone 2017), and Classical Greek cities in 4th Century BC utilizing the idea of solar oriented homes (Butti and Perlin 1980). These principles ultimately drive further the concept of solar envelopes proposed by Knowles (1974). As a contextual and passive design strategy, solar envelopes consist of imaginary building mass determined by considering the amount of desirable sun access without violating surrounding buildings during the predefined period. With a principle of space-time constraint (Knowles 1981), input parameter of solar envelopes can be divided into geographic properties (plot, the distance of surrounding buildings, and shadow fences) and climatic properties (site location such as latitude and longitude, and time limit). These parameters play an important role in determining the volumetric size of solar envelopes.

Furthermore, the evolution of digital tools affects design platforms and methods of solar envelopes, ranging from conventional techniques such as descriptive, profile angle, and 2D orthographic projection (Topaloglu 2003) to computational methods including descriptive geometry (DG), solar obstruction angle (SOA), constructive solid geometry (CSG), and digital elevation modelling (DEM) (Alkadri et al 2018). However, these current methods pose several barriers that may result in missing information during contextual analysis. In most cases, for example, the existing 3D site modelling (e.g., solid modelling (Staneva 2008)) lacks in preserving complex geometry of surrounding context especially when it comes to the isolated and dense areas. Consequently, relevant site properties such as vegetation, material and other temporal site elements are often neglected during the simulation of solar envelopes.

One of the fascinating methods is subtractive form finding mechanism (De Luca, 2017) in which refers to CSG. This method generates solar envelopes by using volumetric samples of three-dimensional matrix or the so-called 3D polyhedral. In principle, the polyhedra are extruded from the proposed land parcel based on criteria of new building such as width and height, functional utilities, number of floors and the like. Ideally, every 3D polyhedron can be associated with one typical room in the real building. This subtractive method, furthermore, involves sun visibility to identify visible sun hours during a selected period. In this way, each polyhedron acts as a 3D voxel carrying information relative to sun access of neighbouring buildings. However, the mechanism of sun visibility becomes challenging when dealing with blocked areas from the sun. The current approach of context modelling merely focuses on the self-blocked mechanism from the existing building's geometry so as to predominantly neglect site properties that might be relevant for sunlight hours simulation (e.g., vegetation). Besides, the existing approach also uses centroid points that represent surrounding windows during ray tracing analysis. These window samples are, however, limited to calculate the entire area of surrounding facades. This study, therefore, attempts to improve the existing workflow of solar envelopes by making use of potential application of point cloud data in capturing the real context.

As a product of 3D laser scanning, point cloud has been extensively used regarding data representation and data analysis in various disciplines such as civil engineering, computer science, photogrammetry, geoscience, and heritage. As a data structure, point cloud indicates a collection of multidimensional points (Randall, 2013). It is usually characterized by spatial XYZ coordinates and is optionally be assigned by typical attributes such as reflection intensity (I) (Weinmann, 2016), color properties (RGB) (Fujita, Hoshino, Ogata, & Kobayashi, 2015), and any additional abstract information. These attributes are, furthermore, used to perform ray tracing analysis, substituting the role of centroid points on surrounding windows. Inclusion of surrounding properties during the simulation will expand the result analysis comprehensively.

In general, the proposed method in this study contributes to several aspects of the cycle of architectural design practices as follows:

- The well-informed site allows architects to construct more possibilities regarding simulation of solar envelopes such as solar collector and other microclimatic analysis. The proposed method simultaneously enhances awareness of architects during contextual analysis so that environmental properties of existing context can be paid more attention within the conceptual design phase.
- Integration between 3D scanning technology and solar envelopes may increase the robustness of the result analysis due to consideration of surface properties of the existing environment.

Furthermore, the following section will describe the computational procedure of the proposed method.

METHOD

This study proposes a computational workflow for generating subtractive solar envelopes based on point cloud data (see Fig.1). In general, the computational procedure is categorized into four sections consisting of input, task, digital tools, and output. Description of each section is discussed in detail below.

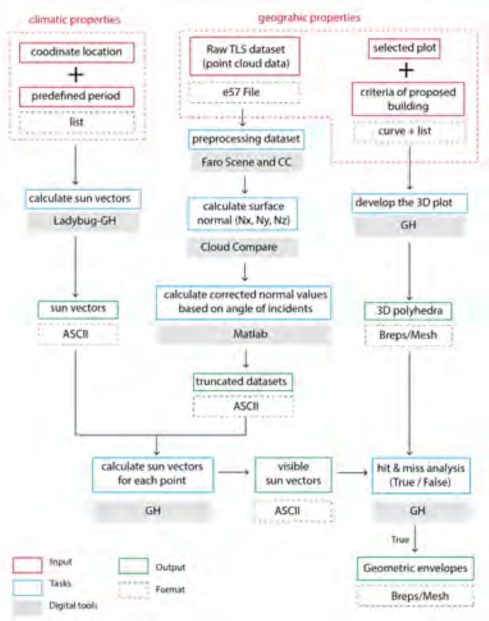


Figure 1
Computational procedure of subtractive solar envelopes

Input

In principle, all input is originated from climatic and geographic properties. Climatic properties are used to calculate the number of sun vectors that will be simulated on each point cloud during the simulation. It is produced according to a specific location within a certain period. In this case, the selected site is located in Groningen, Netherlands with latitude position 53.2194° N and longitude 6.5665° E. The time setting takes a sample of the required period on 21st for each month from May to September, starting from 9 am to 9 pm. With the time step of 2, this setting results in around 25 sun vectors. Meanwhile, geometric properties involve two parts: the proposed building and surrounding environments. The proposed building is represented by 3D polyhedra that consist of 300 polyhedron (see Fig.2). Each polyhedron indicates the dimension of one typical room in the real building, consisting of 3 x 3 x 3 m. It is placed in front of the existing building.

For the surrounding environment, this study employs a small sample of point cloud dataset. It consists of a small portion of building facades from TLS (terrestrial laser scanning) dataset of Middlestum Church in Groningen, Netherlands. The dataset is collected by using Faro Focus 3D laser scanner with wavelength 950 nm. It is also supported by Nikon D5300 for capturing colour properties. The use of TLS datasets principally aims at obtaining more accurate representation, high-resolution formats, and broader coverage of isolated areas in comparing with ALS (airborne LiDAR) datasets. The data provided through these inputs are elaborated within the developed workflow.

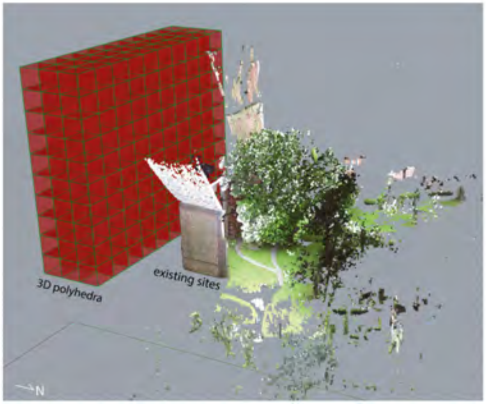


Figure 2
The selected site and 3D polyhedra (land parcel)

Tasks

This section contains a series of specific operations to generate solar envelopes. Some of these tasks can be performed simultaneously such as calculation of solar vectors and development of the 3D plot (polyhedra) due to simple construction procedures, while task of dataset pre-processing and normal values correction need to run sequentially due to the requirement of preliminary input. Some of these tasks are briefly discussed as follows:

- Dataset pre-processing.This task includes outlier (unnecessary cloud of points) removal, dataset subsampling, and conversion of the dataset's format. The use of dataset subsampling permits us to adjust the density of points so as to reduce time consumption during the simulation. In this case, the dataset is subsampled by 5 cm for the distance between points. Accordingly, it results in approximately 449.267 points from 31.5 million of points
- Calculation of surface normal. In order to calculate the normal direction of each point within the dataset, we apply Hough Normal plugin (Boulch & Marlet, 2016) in Cloud Compare (CC) for an unstructured point cloud. In this case, several tolerance angles are simulated to set a variety of normal values from the angle of incidences, ranging from 10° to 90°. A detailed procedure of this section has been addressed in our previous work (Alkadri, Turrin, & Sariyildiz, 2019)
- Calculation of optimal normal values. In principle, some points within a certain angle can correspond very well to the projection of the laser beam during scanning. This affects the distribution of points that show point characteristics at a certain angle. Thus, an evaluation of the scattering points is performed by only keeping the densest cloud from all angles. It simultaneously aims at minimizing erroneous level regarding environmental factors during scanning. In this case, the dataset truncation is set to range between 0 - 0.01 that results in proximately 239.178 total points to be selected for optimal normal values (see Fig.3).

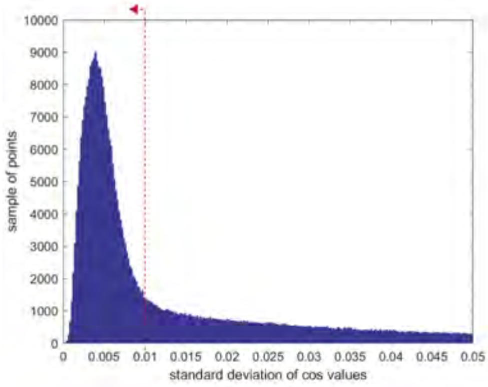
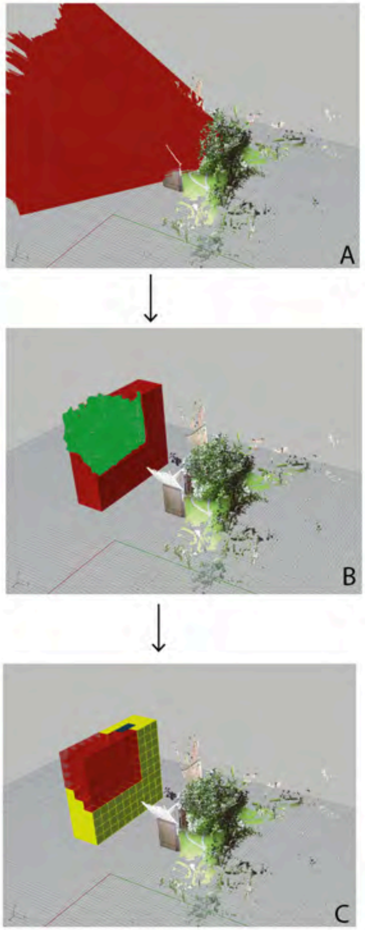


Figure 3
The truncation of the dataset

- Calculation of sun visibility. This step aims at calculating visible sun vectors that will be applied to each point within the dataset. It is done by multiplying sun vectors from the indicated period with optimal normal vectors from truncated points. In order to obtain points that meet the criteria of sun visibility, these vectors are subsequently filtered by considering only values that are smaller than the projected angle of 90°. This is because values that are equal and larger than 90° consist of zero and negative cosine values, respectively. It means that those values exclude within the list of visible sun vectors.
- Ray tracing analysis. This part consists of ray tracing procedure or hit & miss analysis between selected sun vectors, points and, the 3D polyhedra (300 polyhedron). Figure 4A illustrates that selected points for ray tracing analysis are primarily originated from the building façade due to optimized normal values of the dataset. This calculation results in around 110, 7 million of intersections (see Fig. 4B). With a Boolean operation, voxels with "True" values will be used to generate solar envelopes while "False" values are indicated as an obstruction that needs to be eliminated (see Fig. 4C).

Figure 4
Ray tracing procedure A - Hit & miss analysis B - Points obstruction C - Voxels intersection



Digital tools

In general, this study employs various digital tools depending on specific tasks performed within the computational workflow. For examples, 3D modelling and environmental simulation during the generation of solar envelopes are predominantly supported by Rhino and Ladybug component in Grasshopper. Meanwhile, dataset preparation and calculation of surface normal of point clouds in different angles are performed by Faro Scene and Cloud Compare (CC), respectively. Lastly, Matlab permits us to calculate optimal normal values and make a truncation for selected datasets.

Output

According to the workflow presented in Fig.1, several outputs have been generated during the process of simulation depending on the performed specific task in the workflow. These outputs then become input for the following procedure such as sun vectors, 3D polyhedra, truncated datasets, and visible sun vectors. The final output is geometric envelopes that successfully meet the criteria of solar envelopes.

RESULT AND DISCUSSION

As a result of the simulation (see Fig.5), this study presents several findings regarding the final geometry of solar envelopes as follows:

- The total voxels (polyhedron that carries information of sun vectors) that successfully meet the criteria for solar envelopes are 208 out of 300. It means that around 92 voxels are considered as obstruction geometries. These obstructive voxels are subsequently eliminated because of blocking direct sun access to surrounding facades during the indicated period. According to Figure 5, those voxels are averagely located on the above of the 4th floor but remains three full blocks on the Westside. This is because solar vectors produced by predefined cut-off-times and the site location are predominantly toward the Western direction with the incident angle approximately laying between 30° - 60°. In principle, this result can be more robust if we densify solar vectors during the simulation. For example, by increasing the number of cut-off times allows us not only to increase the number of solar vectors but also to generate a broader incident angle so as to widen intersection coverage. This, however, will require high computational cost and

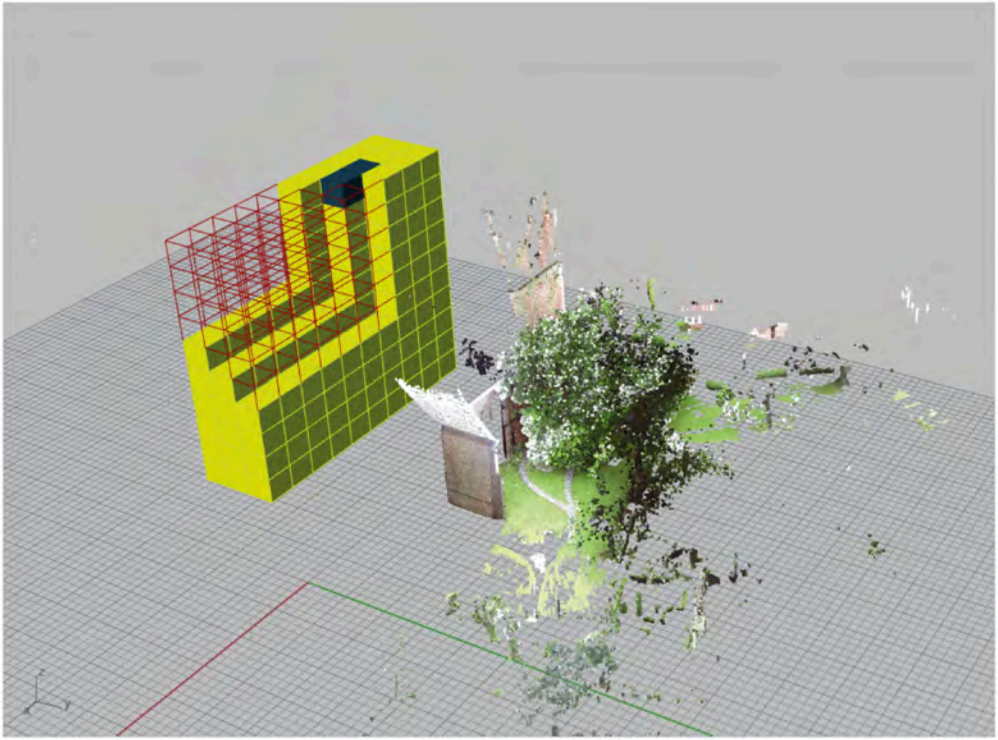


Figure 5
The final geometry
of solar envelopes

time due to hundreds of millions of rays intersection.
- The remaining voxels constitute colour-coded values that show the level of obstruction index, ranging from yellow with 0 obstructions to the light green with medium obstruction and the last, dark green with a high level of obstruction. In this case, Figure 5 illustrates that the polyhedra predominantly consists of yellow colour. Only two voxels are being identified containing medium obstruction index, which is located on the top of the polyhedra. It means that these voxels are potentially violating direct sun access to the surrounding building within this period. When it comes to functional utilities, these remaining voxels can be filled with any building's program that needs direct sun access while for the removed one and light green voxels may be filled with open space and courtyard, respectively.

CONCLUSION AND FUTURE RECOMMENDATION

This study proposes a novel method of subtractive solar envelopes by making use of 3D point cloud data. The proposed method aims at not only compensating missing information during contextual analysis but also integrating existing computational workflow of solar envelopes with geometrical properties of 3D scanning technology. According to the proposed workflow, several concluding remarks can be drawn as follows:

- The use of point cloud data in solar envelopes allows us to extend the functional properties of 3D scanning technology into the architectural design stage especially related to environmental analysis rather than merely as data visualization.
- Calculation of optimal normal values during the dataset processing is used not only to obtain corrected values of point cloud but also to minimize the erroneous level of datasets during scanning.
- Subtractive mechanism of point cloud confirms the feasibility of the proposed method to deal with solar access by including site properties of the existing environment.
- The proposed method can be a starting point to raise awareness of public policies especially related to contextual analysis and microclimate condition for the future development of sustainable architecture and the built environment.

However, some acknowledge limitations need further consideration. For example, the computational issue during the simulation remains a great barrier to perform a huge amount of the dataset. Alternatively, some aspects need particular adjustments such as the number of sun vectors and dataset subsampling. Besides, the inclusion of complex urban properties may enhance the analysis result of simulation such as street, urban scale, and the distance between the land parcel and existing building. This is important because these aspects may influence the intersection of total rays during the simulation so that it can affect the final geometry of solar envelopes.

Furthermore, this study highlights some potential aspects for future recommendation. For example, radiometric information contained in point cloud data can be further explored to integrate material properties of the existing environment with the proposed solar envelopes. This can simultaneously complement environmental performance simulation of new solar envelopes regarding the contextual analysis of the built environment. Moreover, the proposed method can be further explored by using a different climatic context such as tropical countries. This can expand a wide range of design implementation of solar envelopes with different urban settings.

ACKNOWLEDGEMENT

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Development of a Semantic Segmentation System for Dynamic Occlusion Handling in Mixed Reality for Landscape Simulation

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The use of mixed reality (MR) for landscape simulation has attracted attention recently. MR can produce a realistic landscape simulation by merging a three-dimensional computer graphic (3DCG) model of a new building on a real space. One challenge with MR that remains to be tackled is occlusion. Properly handling occlusion is important for the understanding of the spatial relationship between physical and virtual objects. When the occlusion targets move or the target's shape changes, depth-based methods using a special camera have been applied for dynamic occlusion handling. However, these methods have a limitation of the distance to obtain depth information and are unsuitable for outdoor landscape simulation. This study focuses on a dynamic occlusion handling method for MR-based landscape simulation. We developed a real-time semantic segmentation system to perform dynamic occlusion handling. We designed this system for use in mobile devices with client-server communication for real-time semantic segmentation processing in mobile devices. Additionally, we used a normal monocular camera for practice use.

Keywords: *Mixed Reality, Dynamic occlusion handling, Semantic segmentation, Deep learning, Landscape simulation*

INTRODUCTION

Preserving good landscapes is important in enhancing our quality of life. To preserve good landscapes, it is necessary to predict and assess a planned landscape in the project. A landscape assessment means that a project executor hears various opinions from stakeholders and evaluates them (Fukuda, et al. 2014). Then it is difficult for stakeholders, especially non-experts like residents, to imagine the planned landscape in case three-dimensional (3D) objects have not existed yet. According to this context, the visualization of the planned landscape can help stakeholders to grasp the project and will preserve good landscapes.

The use of mixed reality (MR) for landscape simulation has attracted attention recently. MR merges real and virtual worlds (Milgram and Kishino, 1994), and can produce a realistic landscape simulation by overlaying a 3D computer graphic (CG) model of a building that does not yet exist on a camera view of a given area. Augmented reality (AR) is a similar concept that merges real and virtual worlds by overlaying computer-generated information on a real space; however, MR merges real and virtual worlds with high standards whereas AR only overlays information on a real space.

One challenge with MR that remains to be tackled is occlusion (i.e., the relationship between the physical and virtual worlds) (Shah et al., 2012). When physical objects occlude virtual objects, the augmented image may cause user confusion related to depth perception (Figure 1). Thus, it is crucial to handle occlusion appropriately in MR.

Previous studies of occlusion handling methods have been divided into three categories: model-based method, depth-based method, and contour-based method. Model-based methods create a 3DCG model of the real scene in pre-processing and compare the depth of the virtual objects with the 3DCG model to handle occlusion. Inoue et al. (2018) developed landscape design simulation system using MR. This system handled occlusion using a 3DCG model of the surrounding environment created with structure from motion (SfM) technology in pre-processing. In this system, the occlusion problem is solved by not rendering 3D model pixels that are obscured by the occlusion model. However, if a physical object such as vegetation changes its shape over time, it can be difficult to appropriately handle occlusion by changing the occlusion model's shape. Moreover, if the targets are moving objects such as car and person, it can be also difficult to handle occlusion. Depth based methods acquire the depth information of the real scene from a special camera in real-time and compare the depth of the virtual objects with the acquired depth information of the real scene to handle occlusion. Zhu et al. (2010) improved occlusion handling using depth information estimated by matching pixels from a stereo camera. Tian et al. (2015) converted the depth information acquired from RGB-D camera into a 3D model in real-time and handled occlusion. Some methods realized realistic occlusion handling by depth enhancement (Du et al., 2016, Holynski et al., 2018). However, depth-based methods have a limitation of the distance to obtain depth information and are unsuitable for outdoor landscape simulation. Contour-based methods detect and track the silhouette of the real objects and handle occlusion. Tian et al. (2010) obtained the contour of the specified occluding object by interactive object segmentation method, and tracked the object and handled occlusion. In this method, the occluding object needs to be displayed in the first frame, and segmented and tracked with high accuracy. Roxas et al. (2018) used semantic segmentation and a given depth map for occlusion handling. Semantic segmentation image pixels with a corresponding class of what is being represented. This method cannot handle dynamic occlusion because a given depth map is necessary, and also needs to use a high-end laptop computer in outdoor MR simulation because real-time semantic segmentation processing involves heavy processing.

This study focuses on a real-time dynamic occlusion handling method for MR-based landscape simulation. To this end, we developed a real-time


a) Current situation
b) AR with incorrect occlusion
c) AR with correct occlusion

Figure 1
Occlusion problem in MR (Inoue, et al. 2018)

semantic segmentation system to perform dynamic occlusion handling. Our proposed method can extract each object's region and handle occlusion dynamically in outdoor MR simulation. Thus our proposed system can implement more realistic landscape simulation with the expression of the relationship between a 3DCG model and physical objects including moving objects such as car and person and help stakeholders to understand a planned landscape more correctly. We designed this system for use in mobile devices such as standard laptop computers and tablets, thus, it enables client-server communication for real-time semantic segmentation processing in mobile devices. Additionally, we used a monocular camera for this system.

DEVELOPMENT OF A SEMANTIC SEGMENTATION SYSTEM FOR DYNAMIC OCCLUSION HANDLING

Overview of our proposed system is shown in Figure 2. As explained in Chapter 1, we adopted a semantic segmentation technique to handle occlusion dynamically in outdoor MR simulation. Semantic segmentation can extract each object's region frame by frame, thus, it is considered that dynamic occlusion handling can be realized using this technique.

Real-time semantic segmentation processing involves heavy processing and thus requires a high-end desktop computer. However, our proposed system is to be used for landscape simulation outdoors, so it needs to be used on a mobile device. We there-

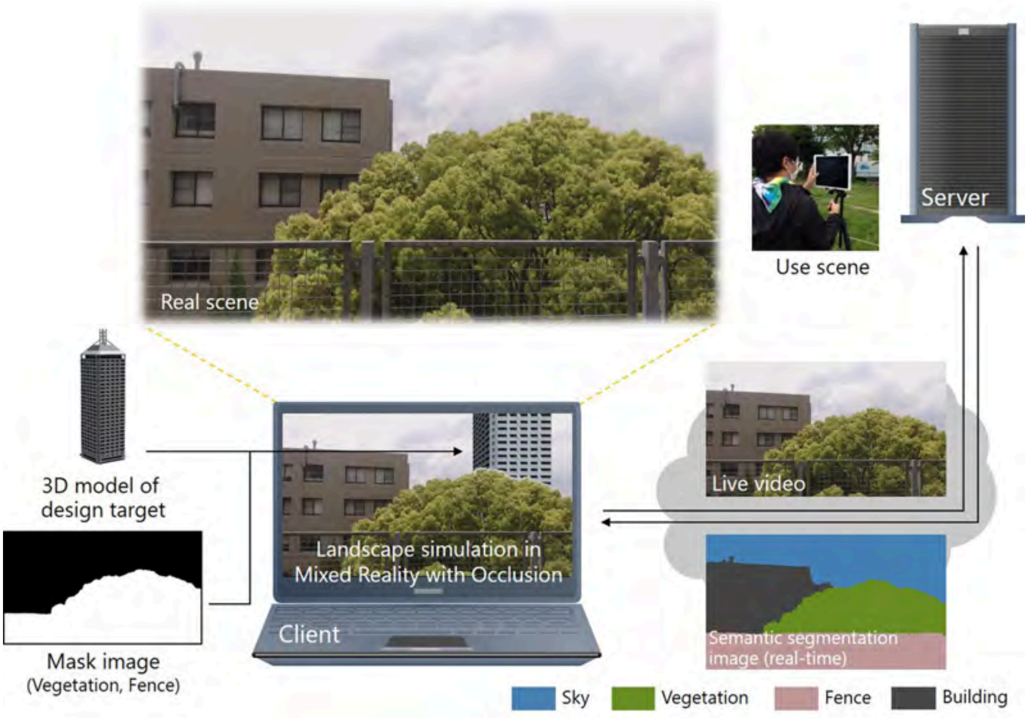

Figure 2
Overview of our proposed system

fore developed a system in which a client device transfers image frames to a server, which performs semantic segmentation processing on those frames and sends processed frames back to the client. Moreover, many semantic segmentation modules have been proposed due to the advancement of computer vision recently. Thus, we designed this system whose semantic segmentation module can be replaced when more sophisticated semantic segmentation module is developed. We used the Unity game engine to develop our proposed system because Unity game engine can implement a Graphic User Interface (GUI) based MR system.

Client-server communication

For client-server communication, we used a Python web application framework known as Flask, which supports the development of web-based services. When a client device connects to the web application on the server it sends an HTTP request, which the server receives along with an image from a camera on the client device. The server then performs semantic segmentation processing and transfers the segmentation image back to the client device as an HTTP response (Figure 3).

Next, we displayed the frames acquired from the client device camera and the segmentation images acquired from the server in the Unity engine on the client side. We used Unity's www class to receive segmentation images from the web application on the server. If the frames acquired from the camera are displayed as is, there would be a gap between those frames and the corresponding segmentation images because of the latency of the client-server communication. Therefore, we delayed and adjusted the display of client-acquired frames to the display of segmentation images, solving this mismatch because was assumed it would lead to inappropriate occlusion handling.

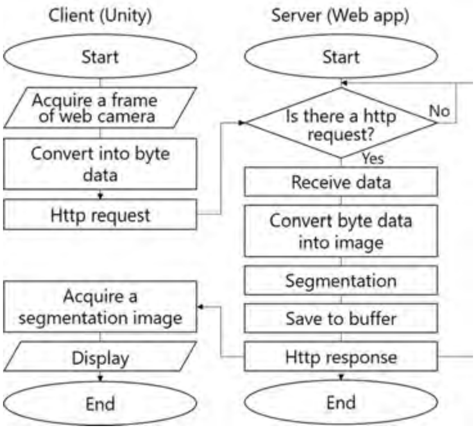

Figure 3
Flow chart of the client-server communication

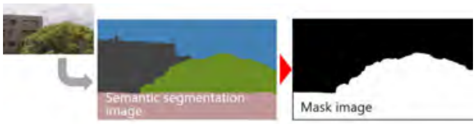

Figure 4
Mask image creation (targets: vegetation, fence)

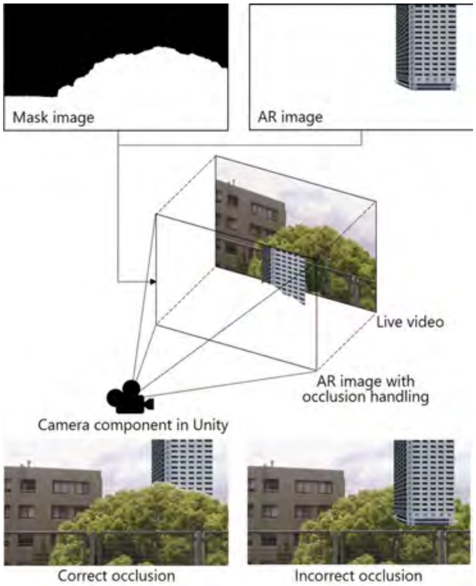

Figure 5
Occlusion handling by not rendering AR image pixels that merged into a mask image

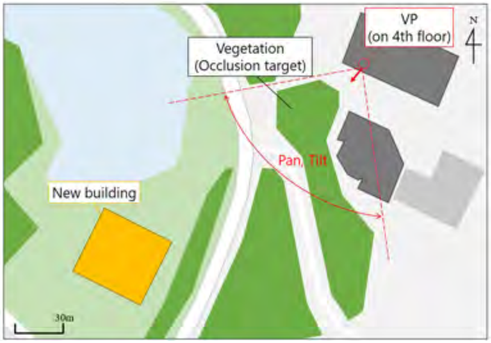

Figure 6
Arrangement of the newly constructed building

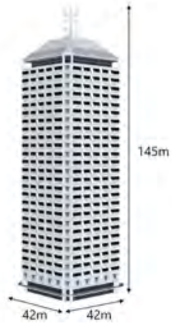

Figure 7
Measurement of the newly constructed building model

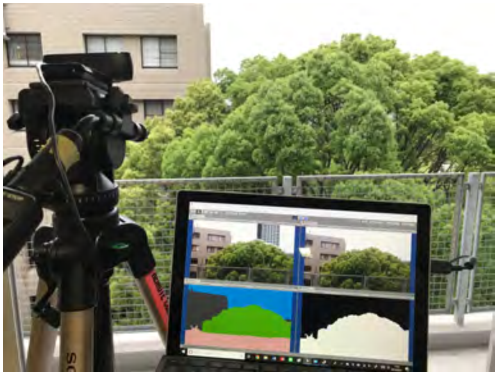

Figure 8
Experimental photograph

Occlusion handling

To implement dynamic occlusion handling, we must create a mask image of the occlusion handing target object. We created a mask image with RGB values in the segmentation image using OpenCV for Unity (ver. 2.2.8), which is a Unity image processing plugin (Figure 4). We then defined an occlusion handling target object and created the object's mask image. We then merged the mask image into an image of a 3DCG model, referred to as an AR image, and handled occlusion by not rendering AR image pixels that merged into the mask image (Figure 5).

VALIDATION EXPERIMENT

We validated our semantic segmentation system for dynamic occlusion handling. We adopted ICNet (Zhao et al., 2018), which is a semantic segmentation method based on deep learning, because of its processing speed and accuracy. We applied the Cityscapes dataset (Cordts et al., 2016), which was created for understanding urban scenes as ICNet's semantic segmentation dataset. We used a laptop computer with Intel Core i5-8250U of CPU, 8GB of RAM, and Intel UHD Graphics 620 of GPU as a client device and a desktop computer with Intel Core i7-8700K of CPU, 32GB of RAM, and NVIDIA GeForce GTX 1080Ti 11GB of GPU as a server device. A Logicool HD Pro Stream Webcam C920 was also used. We acquired frames with 1024×576 pixel resolution from a webcam connected to the laptop and conducted client-server communication over a local area network (LAN) as this was the only possible environment.

Outdoor MR simulation was conducted to validate the occlusion handling of the proposed system. Figure 6 shows the arrangement of the new building and the camera's position and orientation. Figure 7 shows the measurement of the new building model. Then, the viewpoint was on the fourth floor of the building because the server device was equipped on the fourth floor of the building and client-server communication was conducted over LAN (Figure 8). Veg-

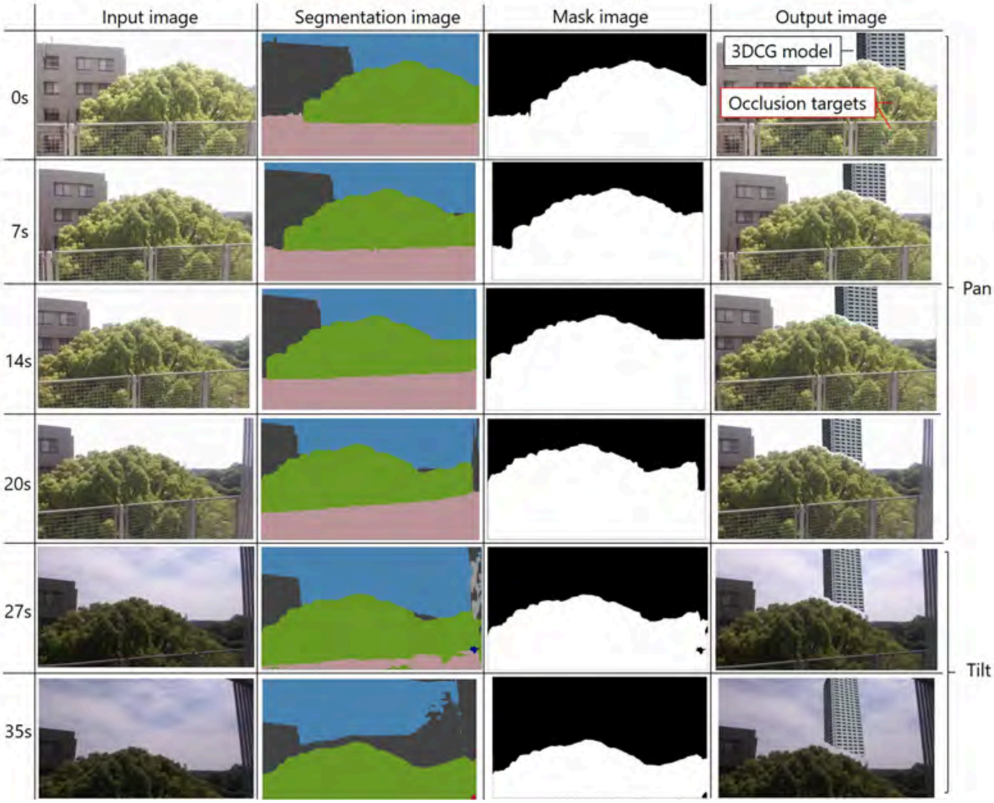

Figure 9
Validation results of dynamic occlusion handling

Figure 10
Labels which can be detected in this experiment

etation and fence equipped on the fourth floor of the building were defined as occlusion targets in this experiment. The webcam was panned in a horizontal direction in the range of the red dotted line of Figure 6 during 20 seconds. After 20 seconds, the webcam was tilted up during 15 seconds. Camera's position and orientation were computed using the method which solves the perspective n-points (PnP) problem and eliminates the outliers using the random sample consensus (RANSAC) method proposed by Inoue et al. (2018). The validation results are shown in Figure 9. Labels and objects which can be detected in this experiment are shown in Figure 10.

From this validation, we confirmed that our system can create semantic segmentation images and mask images using frames acquired from a webcam, thus handling appropriate dynamic occlusion in MR. This system also achieved dynamic occlusion handling using a general mobile device, meaning that this system can be used widely and easily for landscape simulation. However, the processing speed was about 5 frames per second (fps). Processing speed that displays only frames acquired from the webcam was about 30fps, and the processing speed of semantic segmentation with ICNet was about 65 fps. Therefore, it was confirmed that the communication speed between the client-server should be improved. And also it was confirmed that the result of semantic segmentation processing contained false extraction, especially in the result after 35 seconds. The accuracy of semantic segmentation processing should be validated.

CONCLUSION

This research accomplished the following:

- We developed a system which enables dynamic occlusion handling in MR using image processing techniques that create a mask image from a segmentation image and merge that mask image into an AR image.
- We developed a system in which a client device acquires frames and transfers them to a server that implements semantic segmentation processing on the frames and transfers them back to the client device.

Future work should adapt this system to a wide area network (WAN) and Internet environment. Additionally, we should validate our proposed system at an outdoor venue like an architectural project, and also validate in the case where occlusion targets are moving objects such as car and person.

ACKNOWLEDGEMENTS

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Post-flâneur in Public Space

Altering walking behaviour in the era of smartphones

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Smartphones have become an ordinary accompanier of our walks and created new modes of appropriation of public space. This study aims to research these modes by observing the altering visual attention and walking behavior of people using smartphones in public space, and in this way, to reveal the emergence of different types of post-flâneurs. In order to address these aims, 346 (195 females, 151 males) smartphone users were observed in a central public square in Ghent, Belgium for seven days in 10-minute time intervals. Each person's gender, age, number of accompanies and their dominant mode of smartphone usage(s) were identified. Afterward, each person's walking timeline was organized into seconds and coded according to their focus of visual attention in 24 different modes which grouped under the three gaze types; visual attention on the environment, on the environment through the smartphone screen, and on the smartphone screen. Results of the descriptive statistics, multivariate graph, and rhythm-based in-depth analysis show that different types of smartphone activities affect visual attention and speed differently. Different types of post-flâneurs such as navigators and photo takers were identified based upon their high percentage of visual attention on the environment and slower walking speed. The study also revealed the frequent presence of phone-walkers (who walk while only holding the smartphone) and smartphone zombies (who walk slowly and without attention to their surrounding) in public space. In addition to these, our research revealed rapid smartphone zombies who walk faster than the average walking speed, a finding contrary to the former studies reviewed.

Keywords: *visual attention, public space, smartphone, walking behaviour, post-flâneur*

INTRODUCTION

Smartphones are one of the most rapidly adopted technologies in history (Kalin and Frith 2016). By enabling the use of Information and Communication Technologies (ICTs) in mobile mode (mICTs), smartphones have become an essential part of our everyday life in public space and an ordinary accompanier of our walks. Today, more than 65 percent of the world population own mobile devices and over half of them are smartphone users (Intelligence 2017). Countries with advanced economies take the lead with a median of 76 percent smartphone ownership rates and these rates become even higher when it comes to the young adults (Smith and Anderson 2018). A recent survey shows that over 20 percent of young adults use their smartphone during walking (Lennon et al. 2017). The rapid closing of the age gap between smartphone users (Anderson and Perrin 2017; Smith and Anderson 2018) implies that using a smartphone whilst walking will become even more prevalent in the near future.

Empirical studies indicate that using a smartphone while walking can enable sensorial engagement with the surrounding urban space (Frizzera 2015). On the other hand, it can also have adverse effects due to the negative relationship between smartphone usage and attention (Wilmer et al. 2017). Humans switch gazes between the smartphone screen and the urban environment whilst walking. This affects the attention and walking behavior of smartphone users and has been associated with many pedestrian safety problems. The dominant part of the literature on this multitasking activity focuses on these effects (Hartfield and Murphy 2007; Haga et al. 2015; Laurier et al. 2016; Lim et al. 2017; Lin and Huang 2017; Yoshiki et al. 2017; Alsaleh et al. 2018). There is an increasing variety of solutions to address the changing walking behavior such as physical interventions and interface based solutions. Physical design interventions can serve this purpose to some extent. On the other hand, interface-based interventions have proven to be incapable to reduce the risks related smartphone distractions while walking since they take more attention from the environment while expecting to do the opposite (Lu and Lo 2019). In this sense, understanding the altering walking behavior beyond the safety risks and its effects on the appropriation of public space are important to both understand and design the public space of today and tomorrow.

Walking behavior in public space shows itself in different modes with respect to the rhythm, speed and the aim of the walk. While a destination-oriented walker walks with a brisk pace, aimless strolling or ambling are slow activities. These ways of walking are also differentiated within themselves by referring specific figures such as flâneurs who use strolling as a mean of experiencing the city instead of arriving somewhere (Benjamin 1999). Today, with the proliferation of smartphones, we are facing with new figures in public space. Smartphone zombies or smombies who walk slowly as a result of their high attention to the smartphone screen can be listed as one of the most significant examples of these figures. Another emerging figure is the 'post-flâneur' which constitutes the focal point of this study. The post-flâneur who is shuttling between the digital and physical space can be called mainly -but not only- as the "photographer of modern life", walks the city with a smartphone, takes photographs and shares them in the social media (Vlachou et al. 2017).

The increasing use of smartphone use implies that the presence of these figures in public space will continue to increase and new ones will be added. With respect to this, this study aims to determine these new figures of smartphone users among the people walk in public space by analyzing their visual interaction with smartphone screen and the surrounding environment. By analyzing the temporal configuration of gaze shifts through an observational survey, the study addresses the following research questions:

- How do smartphones affect gazes and visual interactions while walking through public space?
- What are the different figures of smartphone

users in public space according to their visual attention and walking behaviors?
- Can we identify a 'post-flâneur' among these figures?

In order to address these research questions, we will present an in-depth literature review on the changing nature of the walking behavior of humans using mobile phones in public space (Section 2). This will be followed by an empirical study in a square in Ghent, Belgium through which 346 (195 females, 151 males) smartphone users were observed between 20 October and 14 December 2018 (Sections 3 and 4). As a result, we will make conclusions on the implications of the results for the future of public space and draw future directions.

BACKGROUND

Observing pedestrians with smartphones in public space

A significant part of the studies on smartphone usage in public space base on self-report data (Exler et al. 2016; Lennon et al. 2017). However, research studies indicate that self-reported usage of smartphone hardly reflects the real use. For instance, a 2015 research showed that actual uses amounted more than double the estimated number of smartphone uses (Andrews 2015). With this respect, observational research is essential to understand the actual use and effects of smartphone use in public space.

The usage of smartphone and its effects on walking behavior in public space is observable since the device itself has mobility in relation to the gestures and actions of the walkers (Laurier et al. 2016). A predominant part of the observation-based studies concentrated on this phenomenon approaches the subject from the perspective of pedestrian safety. In this context, many related studies observe walking behavior of smartphone users in a simulated environment in which they can restrict environmental factors (Haga et al. 2015; Lim et al. 2017; Lin and Huang 2017; Lu and Lo 2018).

On the other hand, there is still a relatively small number of studies on smartphone use in public space. These observation-based studies examine the changing walking behavior of smartphone users in real-world public spaces based on egocentric (Laurier et al. 2016) or controlled (prescripted) walking experiences (Yoshiki et al. 2017). There are a limited number of passive-observation studies that examine smartphone usage in public spaces. A 2010 study on cellphone users in public space focus on talking whilst walking showed that cell phone usage can cause "inattentional blindness" (Hyman et al. 2010). Another passive-observation study held in 2015 (Hampton et al. 2015) revealed that the percentage of people who use a mobile phone in public space is not dominant and people tends more to use a smartphone when they are walking alone comparing to being with groups (Hampton et al. 2015). However, if we think about the rapid increase in smartphone use and the particular interest of this study on using a smartphone whilst walking, the necessity for further research on the topic leaves no room for doubt.

New figures in public space

With the emergence of smartphones, the activities that we are capable of handling while walking with mobile devices has been increased. As navigation became one of the most significant modes of smartphone use in public space with the advances in location-based applications, modes of photo taking and video capturing also became popular with the improvements of camera systems of the smartphones over the years. Modes of texting, reading, talking, and listening still constitutes the majority of smartphone use while walking as in the case of cell phones. Besides these, holding a smartphone without using whilst walking became one of the major modes of smartphone users in public space. With this respect, in the following part of our study, we will examine the existing literature on specific types and characteristics of smartphone users in public space.

Post-flâneur. The modern city of nineteenth-century introduced the concepts of flâneur and flânerie. Benjamin's (1999) 'flâneur', a nineteenth Century character firstly portrayed by Baudelaire, strolls in the city and uses walking as a way of experiencing the city. A flâneur does not have a purpose of getting somewhere, the act of walking is the purpose itself. The basic necessity of a flâneur is the sense of presence and attention to the urban environment and the passers-by and a particular pace which makes a place and what is experienced there, memorable (Connerton 2009). Today, advances in mobile technologies created a new kind of urban wanderer which can be named as 'post-flâneur'. This post-flâneur walks the city with a smartphone, takes photographs and shares them in the social media (Vlachou et al. 2017). This study will try to detect post-flâneurs by examining their walking speed and visual interaction with the surrounding environment and try to bring a new definition of the concept according to these observations.

Smartphone zombie. Besides the post-flâneur, new types of walking behavior can be detected by examining the same variables introduced. Today, the phenomenon of people walking while looking their smartphones is identified as a new character that becomes more and more prevalent at public space and named as "smartphone zombies", "smombies" or "head-down tribe". This new character is a person "who walks slowly and without attention to their surroundings because they are focused upon their smartphone" (Mwakalonge et al., 2015) and associated with many pedestrian safety issues.

Phone-walker. Phone-walker holds the device without using whilst walking becomes one of the observable characters in public space due to its large proportions and a 2018 study shows that the tendency of holding phone whilst walking has a correlation with the gender of the walkers accompanies (Schaposnik and Unwin 2018).

STUDY DESIGN AND THE RESEARCH METHOD

For the purpose of the study, Korenmarkt, a public space from Ghent, Belgium was selected as a case study area. The selection had been made on the basis of the social media usage rates [1], the scale and the movement patterns: Ghent, Korenmarkt. In the context of this research, a defined area of the square had been selected for its appropriate scale for observation of the pedestrian flows. To observe different behavioral patterns of pedestrians using smartphones, 10-minute videos of Korenmarkt square were recorded from the same spot for each day of the week (figure 1). People who walk between designated observation gates with a visible smartphone were observed.

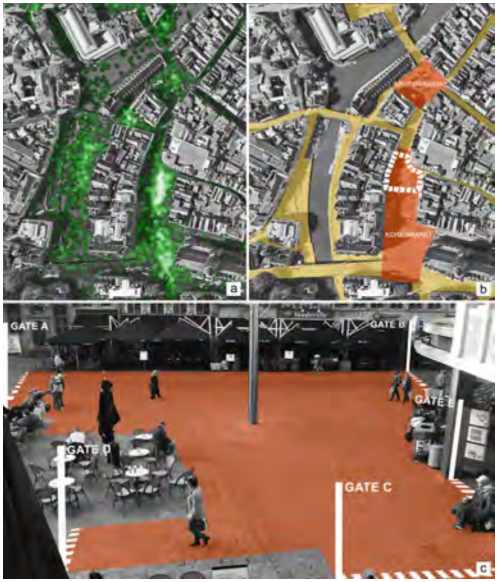


Figure 1
(a) Superposition of Eric Fischer's 6 billion tweets map [1] with Korenmarkt square, (b) pedestrian route network (yellow), public squares (orange) and case study area (white dash line) in Korenmarkt, and (c) defined observation gates in Korenmarkt square.

Eventually, 346 (195 females, 151 males) smartphone users whose total walking path ranges between 26,4 and 33,3 meters (Mean: 31,2 m) observed. Each person's estimated gender and age group, number of accompanies and their dominant mode of smartphone usages were identified. These smartphone related modes were specified as holding, checking, listening, speaking, reading, typing, navigating, photo taking and video taking. Afterward, each person's time spent between their entrances and exits were divided into seconds and coded according to their gaze directions by specifying whether it's a walking or a stationary activity. 24 different codes were created which can be listed under 3 different gaze types; visual attention on the environment, on the environment through the smartphone screen, and on the smartphone screen (table 1).

After decoding, the data were examined by using several methods. This paper presents a summary of the results derived from descriptive statistics, multivariate graph analysis and rhythm-based in-depth analysis for some types of smartphone users in public space. Statistical and graph analysis were completed by using SPSS (v25.0) for Mac OS.

RESULTS

Descriptive Statistics

Results from descriptive statistics show that adult (40%) and young adult (37%) age groups are more dominant among the smartphone users in the Korenmarkt example. Teenagers and elders constitute 15 percent and 8 percent of the users respectively. As opposed to the findings of Hampton et al. (2015) that suggests people tend more to use a smartphone when they are walking alone, this study shows that the number of people using a smartphone while walking alone goes head to head with walking in groups. Even, the percentage of using a smartphone while walking in groups (54%) is slightly more than walking alone (46%).

Smartphone activities. Among the different types of smartphone activities we observed in public space, reading (28,6%) takes the lead which is followed by typing (16,5%), checking (14,2%) and speaking (13,3%) respectively. The high percentage of only holding (11,6%) shows that phone-walkers are one of the emergent modes of smartphone users in public space which needs more consideration as suggested by Schaposnik and Unwin (2018). Navigation (11,6%) which has the same percentage as only holding is another major modes of smartphone usage in public space whilst walking. Photo taking (7,8%) follows navigating and lastly listening (4,6%) and video taking (4%) are the least used modes of the smartphone in walking and transient stationary activities in public space. The low percentage of listening can be expounded by the fact that only people who use their smartphones visibly for listening taken into account during the observations.

Altering movement and objects of visual attention. When the holders (n=40) are excluded from the sample, 27 percent of the smartphone users stopped during their route (n=83) and 84 percent of them used their smartphones during these stationary activities (n=70). Results show that 63,5 percent of smartphone user's visual attention is on the environment (Gaze 1) and 36,5 percent of it is smartphone-based visual attention (Gaze 2 and Gaze 3) in the total walking and stationary activities. The percentages of visual attention during walking indicate similar results. However, if we focus on visual attention during stationary activities, smartphone screen based attention (Gaze 2 and Gaze 3) increases to 54 percent. Our detailed examination clearly illustrated that especially photo taking that focus attention on the environment through the smartphone screen shows itself mostly in stationary activities.

When we examined the average percentages of visual attention and the average walking speed (m/sec) for each smartphone activities, it can be seen that there is a positive correlation between walking speed and visual attention on the environment (Gaze 1), and a negative relationship between walking speed and visual attention on the smartphone screen (Gaze 3). The activity of speaking goes beyond this rule. Although it has a high percentage of visual attention on the environment, it has a slower average walking speed. This can be explained by the fact that although speaking does not take much visual attention, it can create a cognitive distraction (Lennon et al. 2017) which can decrease the walking

Table 1
Codes for different gaze types.

GAZE 1 visual attention on environment		GAZE 2 visual attention on the environment through the smartphone screen		GAZE 3 visual attention on the smartphone screen	
walking	stationary	walking	stationary	walking	stationary
we_gaze on the destination or an accompany	**se**_gaze on an accompany or an object	**wv**_taking video	**sv**_taking video	**wm**_gaze on screen	**sm**_gaze on screen
wd_showing directions	**sd**_showing directions	**wp**_taking photo	**sp**_taking photo	**wso**_sharing own screen	**sso**_sharing own screen
wes_wandering gaze	**ses**_wandering gaze	**wse**_taking selfie	**sse**_taking selfie	**wtv**_speaking on a video call	**sss**_sharing someone's screen
wh_photo and video hunting	**sh**_photo hunting		**spo**_posing for a photo		
wt_speaking on the phone	**st**_speaking on the phone				
wth_speaking on the phone by holding in front of the face					

speed. Besides, navigating and photo taking draw apart from other activities with their high percentage of visual attention on the environment and low walking speed. Accompanied by video taking, they also have the highest percentages of wandering gaze which calculated from the codes of wandering gaze (wes, ses) and photo/video hunting (wh, sh) (figure 2).

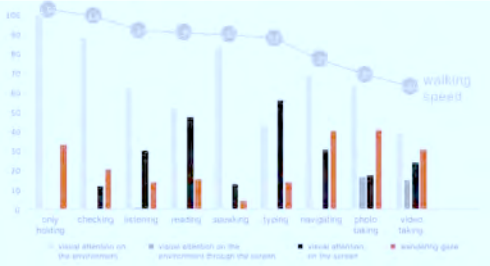


Figure 2
The average percentages of visual attention and the average walking speed (m/sec) for each smartphone activities.

Multivariate Graph Analysis

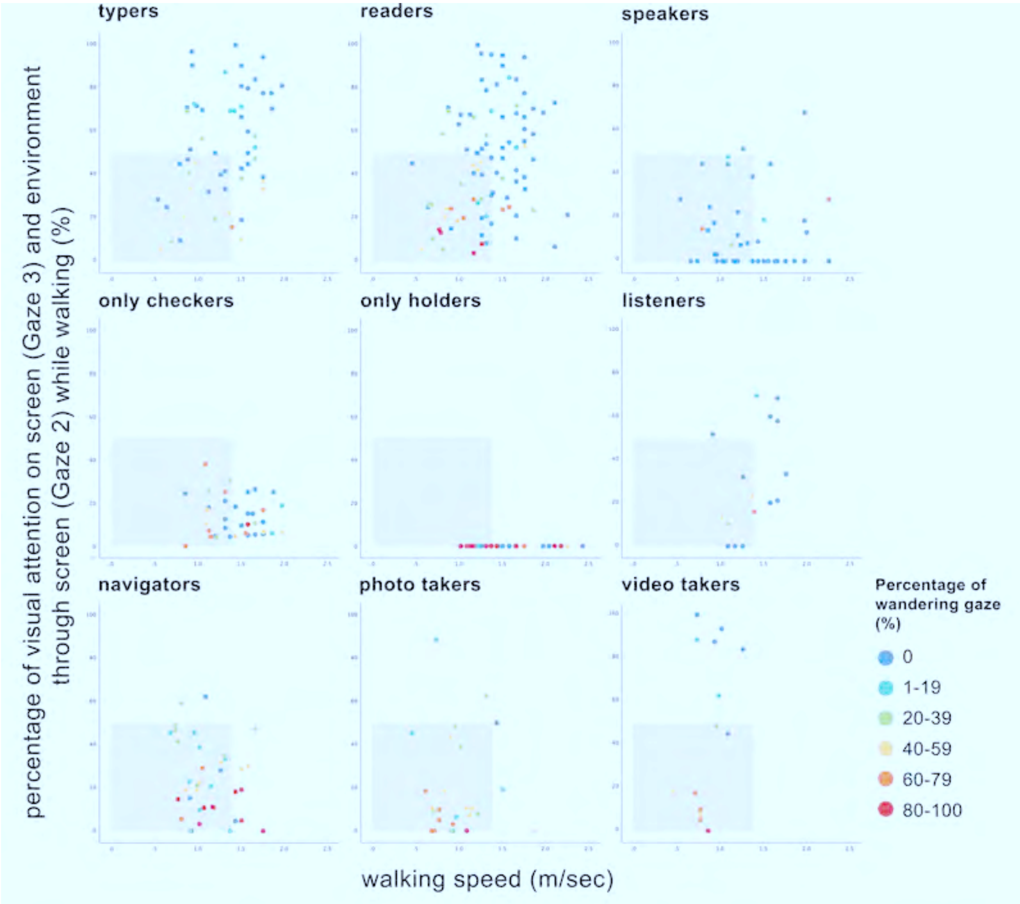
In this part of the study, each smartphone user was mapped in the scatter graphs specialized for different smartphone activities according to their total percentage of smartphone-based visual attention (Gaze 2 and Gaze 3) whilst walking and average walking speed (m/sec). Then, the data were colorized according to their percentage of wandering gaze (walking and stationary) (figure 3). While we focus on the area of the maximum 50 percent smartphone-based visual attention and the maximum 1,4 m/sec average walking speed for pedestrians (grey rectangular), it becomes visible that navigators and photo takers mostly cluster in this area comparing to other users. Readers, on the other hand, sprawl to a larger area that extends over 100 percent smartphone-based visual attention and 2,26 m/sec walking speed. Typers show similarities with readers in visual attention, however, their maximum speed is 1,98 m/sec. Only holders and listeners show resemblance in speed which is higher than 1 m/sec in general. Video recorders clearly constitute two groups in terms of the percentage of smartphone-based visual attention and wandering gaze, and do not exceed 1,4 m/sec average walking speed.

DISCUSSIONS

In this study, we researched new modes of appropriation of public space by observing the altering visual attention and walking behavior of people using smartphones in public space (Korenmarkt, Ghent, Belgium), and revealed the different types of post-flâneurs. We mapped and grouped the smartphone users based on the percentages of smartphone-based visual attention and walking speed graph and colored according to their percentage of gaze wanderings to detect new figures of public space. Results indicated that people using a smartphone while walking can be characterized by analyzing their visual attention and walking behavior.

Post-flânerie is aimless wandering which also involves a high level of gaze wanderings (Gros 2009). When users who have a minimum 60 percent wandering gaze and a maximum 1,4 m/sec walking speed are identified for each smartphone activity, post-flâneurs appear within navigators, photographers, video takers, checkers, and readers. However, if we look at the general distribution of smartphone users according to the smartphone activities (figure

Figure 3
Distribution of smartphone users according to their smartphone activities in the scatter graphs of the total percentage of smartphone-based visual attention (Gaze 2 and Gaze 3) whilst walking and average walking speed (m/sec). Smartphone users were colorized according to their percentage of wandering gaze (walking and stationary).



4), it can be claimed that photographers and navigators are more appropriate to look for a post-flâneur with their general distribution within the desirable interval (percentage of smartphone-based visual attention<50, walking speed<1,4m/sec). For instance, there are post-flâneurs within the video shooters, however, the general distribution of the video takers shows that there is a clear distinction between post-flâneur video takers and video-walkers whose visual attention is highly on the smartphone screen and experience environment mostly through the screen.

This study also proves the frequent presence of smartphone zombies in public space and suggest that smartphone zombie is more than a buzzword. We detected two kinds of smartphone zombies in public space. The first one walks with dominant attention on the screen (attention on screen is more than 80 percent) and walks slower than the average walking speed (1,4 m/sec) as the definition of the term indicates. On the other hand, there is also another kind of smartphone zombie who walks with immense attention on the screen and faster than the average speed. Figure 3 clearly shows that these rapid smartphone zombies mostly appear among readers and typers, while smartphone zombies emerge mostly among video takers who we call as video-walkers whose visual field is restricted by smartphone screen during the whole walk. We also observe that all of these (rapid) smartphone zombies walk through a straight route without any turnings.

The smartphone users in the area between (rapid) smartphone zombies and post-flâneurs varies between immersed to destination oriented walkers. The users who have maximum 40 percent smartphone-based attention and walk faster than the average walking speed are mostly constituted by checkers who give their visual attention to their smartphone screen for short periods. Rhythm-based in-depth analysis of the types of smartphone users also shows the varying timelines of different users on the same route depending on the smartphone activity (figure 4). Examples among the different types of smartphone users in public space show how visual engagement with the surrounding can change according to smartphone activities. It also shows that there can be varying types among the users of the same smartphone activity. For instance, figure 4 shows how a photographer and a photographer post-flâneur differentiates from each other with respect to their focus of visual attention. While the former one immerses into smartphone before and after the photo taking activity, the latter one gives his/her attention into the environment with a high percentage of wandering gaze. It can be claimed that while the former one uses smartphone and photo taking as the aim of the walk, the latter one uses as a tool for the experience.

CONCLUSION AND FUTURE DIRECTIONS

Visual stimuli have been increasing in our surrounding urban environment for a long time and smartphones by rapidly penetrating our everyday life, have been becoming another stimulus that take more and more attention every day. Even though smartphones can give its place to another technology in the near feature, it seems like the demand for our visual attention in public space will continue to increase. When this is the case, understanding the effects of these mobile devices on our visual attention and examining how the interactions with smartphones transform the walking behavior in public space became important to understand changing needs of public

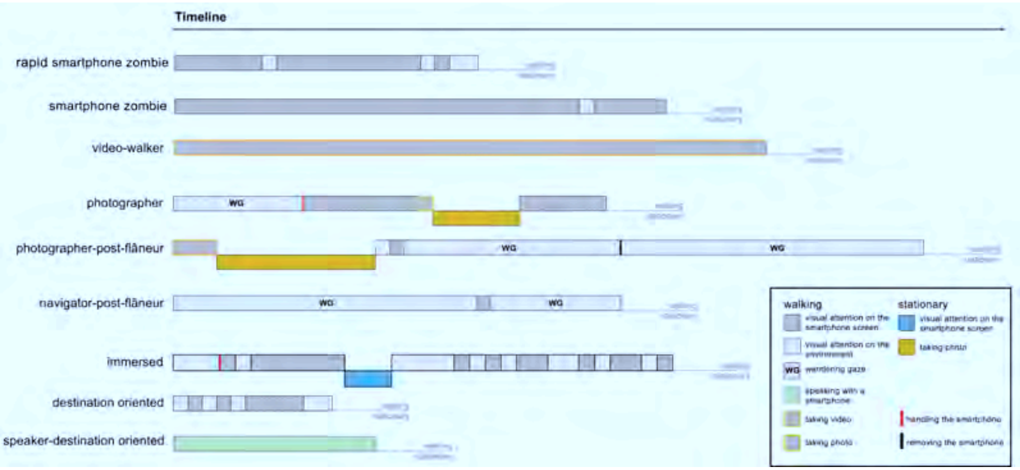


Figure 4
Rhythm-based in-depth analysis of the different types of smartphone users who walk through the same route.

space design.

In line with the former research, this study claims that different smartphone activities affect visual engagement with the surrounding environment and movement within the public space differently. The individual users of the same activities vary within themselves according to their visual attention to the environment and walking speed. By examining these differentiations, this study claims that possible post-flâneurs can be detected mostly among photographers and navigators. According to the same logic, smartphone zombies who gave their attention to the screen whilst walking can be detected among readers, typers, and video-walkers. Results of this research show that smartphone zombies walk in the routes that they do not need to turn and also a significant part of them are walking more rapid than observed in former studies.

Recognizing these new modes of appropriation of public space raises questions on their design implications and possible approaches addressing the emergent "post-public" space. In this sense, this study suggests three strategies towards the phenomenon of the rapid adoption of smartphone in public space.

Taking back the attention: The configuration of the space creates the movement (Hillier and Hanson 1989). While a connected space relieves the movement and can be desirable for a well-designed public space, (rapid) smartphone zombies within this study presents how these walkers show up in the straight routes in which they can move without any attention to their surroundings. With this respect, *breaking the cognitive routine* of the pedestrians with smartphones can be a solution especially in critical locations where the visual attention is vital. With this attempt, the visual attention of the head-down walker who acts by rote can be drawn back to the environment. *Designing spaces for wandering* is also a significant tool. Decreasing the speed increase engagement with the surrounding. Public spaces should be designed to provide more spaces that promote decreasing the pace, wandering through and being stationary.

Becoming the object of hybrid attention: It is clear that humans are getting more and more connected to the virtual world and they bring this virtual space into the physical space with the help of developing mobile technologies. This means the public space of the future should be regarded and designed not only as a physical construct but instead as a *hybrid construct* in which the public space itself can turn into an information technology which can raise smartphone users heads towards the public space and improve the engagement.

Going beyond the visual: Although this study did not focus on audial attention, our reflective observations show that audial stimulants play a significant role in drawing visual attention to the environment. In the Korenmarkt example, street music (in Saturday example) in front of the statue in the middle of the case area drew visual attention of the passers-by from their smartphone screen. In the era of increasing visual stimulants that fights for the visual attention, it is important to due consideration and rethink the *soundscape* (Schafer 1993) *design of public space*. This can be also an important tool to create more collective forms of audial spaces in the era of individual listeners who walk through the city in their personal "mediated urban isolation" (Bull 2012) balloons.

These strategies can be enhanced with a further research on examining altering attention (visual, audial and cognitional) and engagement with the environment from the egocentric perspective of the smartphone users. The rapid penetration of smartphones and location-based applications into public life and its effects on human behavior and public space show that there will be challenges such as privatization and commercialization of the experience. However, by understanding these altering experiences we can rethink the design of public space and improve the relationship between human and their environment and overcome these challenges.

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Dexterity-controlled Design Procedures

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This paper explores the development of design procedures in relationship to their digital proceedings, in order to interface human movement and parametric design procedures. The research studied the use of Leap Motion controller, a gesture recognition device using infrared sensors combined with time-based generative tools in Rhinoceros Grasshopper. A physical, artistic procedure was used as a reference to model a digital design procedure, including a series of parametric definitions combined with them in an attempt to produce complex three-dimensional designs in real time. In a later stage of this research, a modular, open source, digitizing arm was developed to capture hand movement and interact with an autonomous parametric definition, augmenting even more the range of applications of dexterity-based digital design. The challenge of this experimental investigation lies in the negotiation of the designer's needs for a complex yet open design process and the possibilities of defined soft- and hardware solutions.

Keywords: *digital design, dexterity, parametric design, motion detection*

INTRODUCTION

The utilization of gesture-based control is embedded on the digital architecture´s history since Sutherland´s first explorations in CAD technologies. Before the invention of the computer mouse and graphic interfaces, Sutherland developed a light pen that worked directly over the display and called the drawing commands using switches and knobs. Besides being a breakthrough at the time, Sutherland´s Sketchpad was still related to the physical act of drawing, and the procedure he developed actually enhanced the user´s drawing capabilities like zooming or copying.

The invention of the computer mouse and the command prompt eventually drove away these experimental devices in architecture, focusing on creating methods for precise and quick drafting combining graphic interfaces, mouse movements and keyboard commands rather than a creative approach to form generation. Other artistic disciplines like illustrators or digital sculptors made use digital drafting equipment intensively.

For the last two decades and perhaps more, architectural research in the field of digital design tools focused on algorithmic tools and their derivatives: NURBS, scripting, parametric design, genetic algorithms, away from handmade form. Fuelled first by the popularization of personal computing and then by the advancements in digital fabrication, the center of attention was set on geometry: how to control it, how to represent it, how to manufacture it.

Scripting and parametric tools are key tools of this paradigm; complex geometrical compositions are generated and controlled by a series on intertwined values, variables and parameters. Form is created by repetition, translation, displacement, pressure, weight, self-organization, swarms and many other mathematically defined techniques. Control is the keyword: every geometrical aspect of the design is governed by a numeric value, a slider or a mathematical formula.

A common critique to this approach rises in regard to authorship and the role of the designer; there is a frequent sensation that the more (geometric) control we exercise, the more freedom we gain yet the authorial oversight seems to diminish. The designer usually takes the role of a breeder or a collector, selecting the best option out of many computer-generated variations.

This still is opposite to an analog design process which is, in most cases, a creative act. This act is accompanied by an immediate, often implicit reaction to the material and its properties. Throughout the digital design procedure most of the times there is a lack of material and time based response, a spontaneous feedback through the soft or hardware. With this research, we aim to contribute to fill this gap between a purely digital design methodology and the requirements of a real-time, hand-controlled, complex process.

On this regard, this paper explores how to generate complex geometries by using motion sensor devices in order to capture hand movement and incorporating it on a parametric definition. The purpose is to capture human movements, acceleration and dexterity and translate them to algorithmic values in order to generate and control detailed geometry.

The questions that this research proposes are: Which hidden design possibilities arise from capturing human movement into a design process? What is gained and what is lost on this translation procedure? And finally, is it possible to code these movements, automate and optimize such processes in order to reuse them?

STATE OF THE ART

The interest of this research is to capture human movement, either with optical or mechanical sensors and incorporate in a design process. For this matter we use a parametric design environment (Rhinoceros Grasshopper) and sensors like the Leap Motion infrared sensor and a self-developed device similar to a digitizing arm. By using these tools, it is possible not just to capture movement but also to augment in real time it in order to generate three-dimensional form.

There were several attempts to capture human movement and digitalize it in a design environment with a considerable amount of precision. These projects can be divided by the type of sensors they use and therefore, the type of movement they can capture. For example, the use of infrared cameras and body sensors like the Microsoft Kinect can capture the entire body with a relatively good resolution, however they cannot capture precise finger movement. On the other hand, devices like Leap Motion can detect and identify hand and fingers with considerable accuracy, yet the overall position of the hand is sometimes faulty.

Sketch furniture (Front Design 2006) is an interesting example of a design process based on body movement. On their project, an operator would freely sketch a three-dimensional line in space by moving his or her arms on the air, while infrared sensors capture the movement and design software converts the drawn lines into 3d solid ´pipes´. On a second step, these 3d bodies are manufactured with rapid prototyping techniques and can be used as furniture, like chairs or lamps. With this method the user can design tables, chairs and tube lamps by moving his hands, similar to drawing on the air. The Swedish studio uses an array of infrared cameras distributed on a room in order to produce the motion capture.

The ´L'Artisan Électronique´ installation by Unfold (2010) uses laser sensors to capture the hand´s position in order to generate vases by a rotational movement, similar to the ceramic ones created by a turning table. On this project, a linear laser is projected against a surface and when it is intercepted by hand movement, the profile is captured by a camera and digitalized. The two-dimensional line is interpreted as the profile of the vase as it rotates, shaping its form in real time. The importance of this project for the research is that it operates by translating a physical artistic procedure (pottery turning) into a digital method of form making providing a real-time, visual feedback to the artist.

The ´Digital hammer´ project by K. Hinton, also works on this direction but somehow indirectly. The intention of the researcher was to convert human movement into a software tool or modifier, functioning like a real hammer, but operating on a digital body. This way, when the artist hits a physical object with the sensor, the digital body is deformed. The artist developed a device and a software interface as an experimental "digital hand tool", intending to create an accessible tool for manipulating metal bodies within a digital platform, producing unique, unachievable pieces with other methods.

It is also important to state that on both cases, the sensor information is coded into a closed design system: the first one in a sketch-based 3D-pipe and the second one, a revolution-type solid. Both projects lack any sort of material constrains, and since the movement is unrestrained, there is no haptic feedback that can influence or limit the design, something that Hinton´s digital hammer provides. On the case of Front´s project, the artist moves the hand, arm and body in the air with no spatial reference other than his body and his own memory. Although they are not closed-source, both devices were specially created for that specific task and did not seem to be integrated into other design procedures.

On the other hand, there are special sensors which are commercially available and open-source, allowing designers to alter them and to include them into larger, more complex and more flexible design procedures.

Several research teams have developed gesture-based applications using commercial sensors like the Kinect (Microsoft), Leap Motion and the Wiimote tracker (Nintendo). The use of sensory devices such as Kinect and LeapMotion was also used to investigate complex hand sign recognition in real time (MARIN, 2014).

The research of motion detection sensors is also relevant to this research but our aim is to include them into a wider, more open design framework, such is the case of Rhinoceros Grasshopper. Grasshopper is a popular parametric design plug-in that works as a plug in on the Rhinoceros software, based on NURBS technology. Its extensive use in design and architectural applications make it an interesting choice to effectively interface gesture recognition within a design procedure.

Another interesting application of motion detection is made through the use of digitizing arms. They are often used to scan objects in three dimensions by locating points using an articulated arm. These arms often have three, four, five or more axes in order to accurately locate its tip in space.

Andrew Payne developed a 5-axis digitizing arm to control a 5-axis robot in real time using a similar technique, through the Grasshopper interface (Payne 2011). The digitizing arm works a scaled copy of the segments and articulations of a robot arm, this way the control is directed by the user and mimicked by the robot in real time using a FTDI chip as interface. On a later stage of this research, we designed a modular arm using Arduino microcontroller and angle sensors with the intention to create a modular, upgradable design.

OBJECTIVES

The intention of this research is to include hand motion and dexterity into a wider, flexible design methodology. Apart from sketch applications, the idea is to effectively use motion capture information to produce complex results, impossible to achieve by other means within a design environment. For this matter, we have designed several custom scripts or small programs that act as design procedures, performing a series of geometric operations using hand and finger movement as input data.

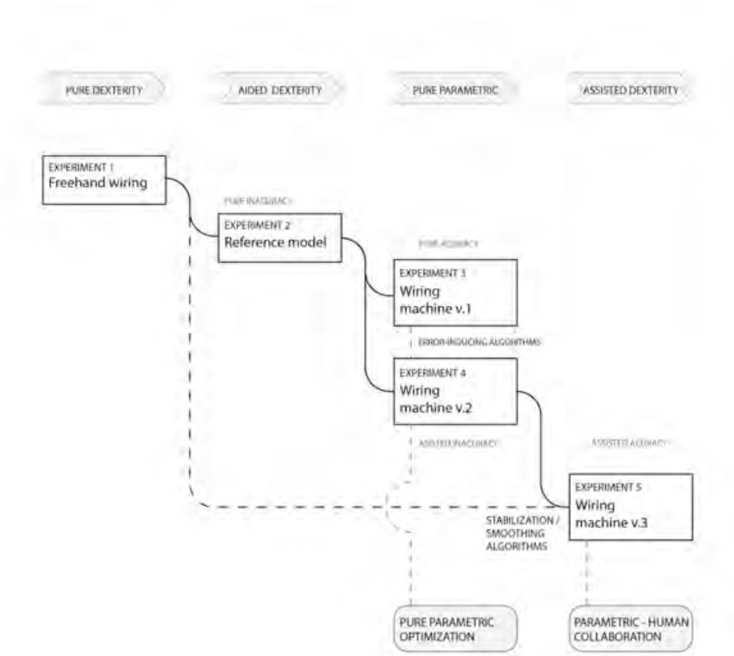


Figure 1
Design research method

The idea of this study is to bring together the advantages of both approaches, manual and digital. Our research intends to study and mimic manual procedures performed with digital environment, aimed towards a better understanding of both types of procedures, finding their limitations and opportunities.

Instead of using the hand movement to draw lines freely like Front´s Sketch Furniture project, our research intends to tracks hand and fingers and then mount a set of geometrical tools on top of them. This way, the digital procedure does not only consist on capturing hand movement but also includes stabilization algorithms, drawing presets and self-generating geometry.

On these terms, devices like Leap Motion have proved an interesting exploration tool but also evidenced a limited functionality in terms of precision and feedback, since they use an array of infrared cameras to detect fingers and articulations. The user has no physical feedback about where the hand or finger is in the three-dimensional space, nor a precise idea of what is he or she drawing in space. Unfold´s project (Unfold 2010) deals with this issue partially by allowing the user to draw a flat line in space. This line is projected towards a plane and will be in turn be used as a revolving profile, limiting the drawing to a two-dimensional task. This simple geometric procedure marginally improves formal control and feedback.

The combination of new tools, which respond to manual dexterity (Grunwald 2016) and software instrumentalization aims to improve a digital workflow. We operate under the definition of dexterity as a degree of ease, speed and accuracy of human actions (Froehlich, and Drever 1983); this also includes a better awareness and understanding of spatial conditions and precise use of those tools throughout the design process.

For this reason, at the Faculty of Architecture, RWTH Aachen University, J.Meyer and F.Garrido have developed extensive experiments on these algorithms using sensors, of which first results were presented and discussed on the RCA Conference at TU Kaiserslautern in 2018 for the first time. At a later step the team designed and developed a 5-axis digitizing arm in order to improve precision and add more design features to the drawing procedure.

RESEARCH PROCEDURE

The research consisted in translating dexterity-based procedures into a digital design environment, by gradually using sensory devices, micro-controllers and parametric design software (Fig. 1). As a first step, the manual method or procedure was analyzed, then, it was translated into a digital environment and finally a common framework was developed to include both "artistic" methodology and a digital, autonomous one. The intention is to produce novel design techniques that can benefit directly from the designer´s skill and abilities, impossible to produce by standard digital means.

The first assignment of this research consisted on studying and analyzing a procedure, based on a material-related task. As a first example, we studied the artist Joost Meyer and his ´Shark´ series. This group of sculptures was fabricated with metal wire rolled around a substructure on different sizes. They were selected because these works are procedure-based, they cannot be projected with precision since their final form depends on the execution of a task, influenced by materials and a shaping process.

Meyer first creates a wooden structure according to the shape and proportions of each particular fish and then proceeds to roll up metal wire (of different diameters) around the structure. The steel wire takes the form of the fish by adjusting itself more or less precisely to the shape of the wooden parts. Finally, the wooden structure is burned exposing the wire and some of the burnt remains.

The process is time consuming not only because of the size (some sharks are on a one to one scale) but also because of the rolling procedure using a continuous wire; the weight of the material, its resistance to bending, and elasticity difficult its manipulation (Fig. 2).

Figure 2
Burning shark, Joost Meyer, 2017

The purpose was to study the wire´s movements, particularly in relation to the complex shark geometry. Sharks have a longitudinal shape which determines the main direction of the rolling movement. The presence of fins (dorsal, pectoral and caudal) forces Meyer to change the ´rolling´ direction in order to precisely mimic each shape. Material properties like stiffness and ductility need procedure is based on dexterity, experience, craftmanship, and material knowledge.

A second task involved the study of Leap Motion, an input device originally designed for virtual and augmented reality applications. The device uses stereoscopic infrared cameras in order to track the movement of both hands; it can recognize fingers, palm orientation and some gestures such as pinching or grabbing. The integration between the Leap Motion controller and Grasshopper is made with two plug-ins, one is Primate (specifically designed for the controller) and Firefly (also used to integrate with other microcontrollers like Arduino). Thanks to this integration, Grasshopper can interpret the hand as three-dimensional geometry; the fingertips and finger joints as points, the hand palm as planes, and bones as lines. It is noteworthy that the Leap Motion

Figure 3
Shark sculpture by
Joost Meyer

device was intentionally designed to be mounted on VR goggles following its movement, but it also works standing on a fixed base. Because of this, the result is that there is a range from which the device can capture fingers with relative precision; when the hands are moved further away from this range (which is around 50-70cm) the detection becomes imprecise. This limitation needed to be included on the design procedure.

The third phase consisted in the design of a parametric definition that identifies an index fingertip and uses it to draw in a three-dimensional environment. Leap Motion can capture all five fingers from each hand but for the purposes of this research, the use of more than one finger proved to be unnecessary. The definition is fairly straightforward as it captures the position of the index finger two hundred times per second, stamps a point on each location and then draws a line connecting them.

This phase was useful to test the controller and its capabilities, as the result is a doodle-like curve drawn in three-dimensional space. This result is also similar to the above-mentioned Sketch Furniture project, only on a smaller scale. Several iterations of this definition were tested, changing the sample rate and averaging algorithms in order to ´stabilize´ the finger´s position into a more fluid movement.

There are several problems from this approach since the capturing device is not one hundred percent accurate and sometimes, there is not direct line of sight between the sensor and each finger. There are a number ways by which these smoothing algorithms work; either by reducing the number of readings per second, or the ´stamps´ on space, or by averaging the continuous stream of data.

By altering these parameters, the shaky lines began to smoothen into more NURBS-like curves. Here is yet another procedure from which we can smooth the result of the drawing. By generating a 0-degree NURBS curve, the connection between each point is direct, defining a polyline with multiple segments. If we increase this degree parameter, the component uses the points as ´weights´ which pull the curve, resulting in a smoother curve. The higher the degree,

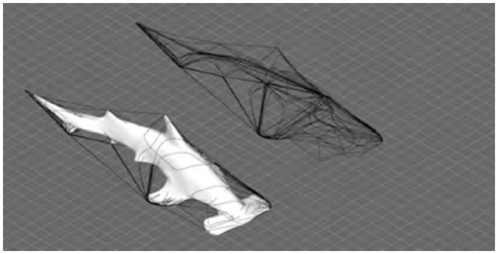


Figure 4
Working in Rhinoceros environment with mesh structures and wiring machine, F. Garrido and J. Meyer, 2018

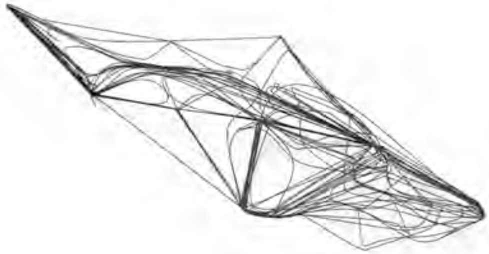


Figure 5
Dexterity based form generation, F. Garrido and J. Meyer, 2018

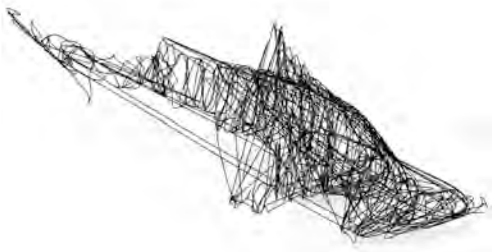


Figure 6
Human parametric design collaboration for form generation, F. Garrido and J. Meyer, 2018

Figure 7
Shark evolution. From hand drawing to computer generation

the smoother is the result, but also, more imprecise, as the resulting curve avoids the points defined by the hand.

A digital design process involves the translation of material properties into digital parameters. We could theoretically use this geometric characteristic of NURBs curves as an analogy for material behavior. We used curve types and sample rates to emulate material behavior. To complete this material understanding, it would be necessary to consider and include manufacturing information into the process as well.

A number of combinations of these algorithms were tested in order to strike a balance between smoothness and precision. Several 3D-sketches were made with this procedure, however lacking any sort of haptic feedback, spatial reference or any other sort of guide apart from the visual, the result relied more on the user´s dexterity than a robust, controlled drawing framework.

For this matter, we decided to imitate Meyer´s procedure and work with a substrate, a base model to which the hand drawing could compare to. An organic mesh was inserted in the work environment, much like the shark´s wooden structure in order to guide the user and his movements on the three-dimensional environment. This base mesh was scanned from a previous Meyer sculpture, remodeled, re-topologized and imported into the Rhinoceros environment (Fig. 4).

The final definition would use this base mesh as a support structure, projecting the hand drawn wire to it, adjusting the drawing lines to its shape, much like Meyer´s wire. The precision of this projection can be altered along with the ´resistance´ of the wire, allowing the exploration of even more aesthetical effects. The degree of which the hand drawn lines attach or detach from the base mesh can be calibrated in order to obtain figures more or less resembling to the original sculpture (Fig. 5). On this procedure, user´s dexterity and the characteristics of the sensor are the keys to a successful design: direction of movement, acceleration and perception of the sensor may alter the design significantly.

The next step consisted in the creation of a definition that performs Meyer´s procedure autonomously. The basic procedure is similar to the one previously described: a wire-rolling process that translates from one end of the fish structure to the other, creating a wire-cage structure mimicking it substrate. A time-based definition with movement controls such as speed, precision, and direction was implemented, operating either lineally (along an axis) or following a predetermined path. Similarly, the degree of precision with which the wire sticks to the substrate can be altered, along with several other factors like the speed of the machine or the curve´s precision and degree.

Finally, a combination of the last two definitions was developed with the main characteristics of the in mind: on one hand, the creative possibilities of free-hand modeling and on the other, the precision and versatility of computer generated procedures. This definition places a wire-bending procedure at the user´s fingertip by using hand location to move the wire bending apparatus while the rolling movement is active. This way, the user can position the wire three-dimensionally and decide in which direction the wiring procedure is performed while the base mesh remains in place (Fig. 6).

This definition provides even more detail and creative possibilities since it allows the user to re-orientate the wiring direction in order to adjust it to the form he wants to cover, which becomes particularly useful in areas like fins and other parts (Fig. 7). Similarly to other previous definitions, the lack of feedback and location makes the wiring process occasionally difficult. A similar definition was also developed, but this time, the user´s hand moves the support mesh while the wiring machine stays in a fixed position.

The combination of hand movement and time-based, form-generating procedures unlocks many potential creative uses, for artists and designers as well. Another example of such methodologies is another experiment that uses three-dimensional blocks as a drawing material. This way, the user draws by adjoining 3d shapes next to each other rather than a continuous line or pipe.

HARDWARE DEVELOPMENT

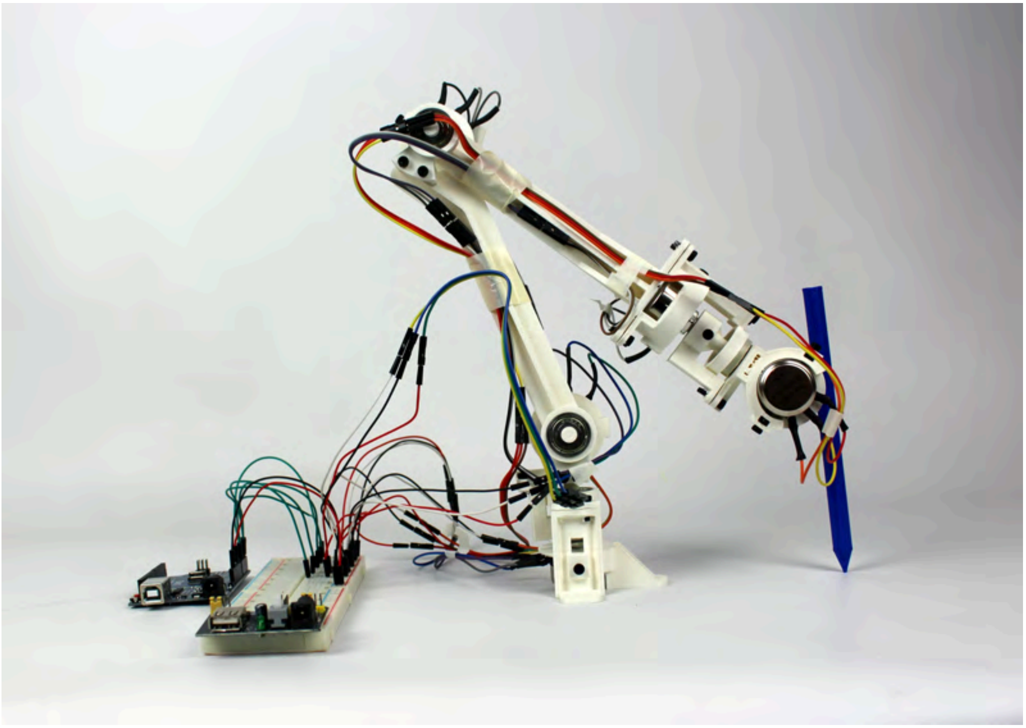
A later step of the research consisted in the development of a ´digitizing arm´ device in order to capture movement with more precision. Using a mechanical device instead of an infrared one (such as the Leap Motion) brings several advantages such as improving precision and avoiding interruptions from other objects, light conditions or the identification of the hand itself. It also provides an interesting feedback since it requires the user to move a physical, articulated object in space in order to reach certain points and positions. The mechanical arm allows a basic spatial awareness of a different kind than just moving arms and fingers on the air.

The design of the arm is based on a 5-axis robot, providing enough freedom of movement in space, without much mechanical resistance. Instead of actuators, on each articulation there are potentiometers or angle sensors, which are connected to a microcontroller communicating with the parametric software.

Using an open source microcontroller like Arduino allows multiple points of personalization and modification in a continuous prototyping process. For example, angle sensors can be replaced for more precise ones when they become available or the arm´s proportions can be altered to fit certain design requirements. In fact, since the design is based on open source materials and modules, the digitizing arm can be scaled to any size and allow the attachment of different tooltips or other articulation configurations.

The device works by logging angle data from each articulation, recreating a digital version of the arm in Grasshopper in order to detect the tip of the digitizing tool. The necessary calculations translating angle information to three-dimensional position-

Figure 8
5-axis digitizing arm
by F. Garrido, 2019



ing is made in the design software; this way, angles and positioning can be stored or modified in real time allowing even more personalization. In fact, the arm can also be used for example, for scanning three-dimensional objects by storing point portions in space or drawing isocurves. This is yet another opportunity to use capturing devices creatively.

The intention of the research is then to make design processes even more flexible both in software terms as well as with hardware components, where modularity and interchangeability are key concepts.

CONCLUSIONS AND FUTURE STEPS

The introduction of gesture-based control is embedded on the digital architecture´s history since Sutherland´s first explorations in CAD technologies using a light pen. This study is linked to other attempts to improve communication between digital tools and designers through design processes and devices. While creating the wired silhouettes of a shark, new perspectives on creating form emerged as the negotiation between designer and scripter lead to an inspirational cooperation in the use of tools and a common design ambition.

The development of procedures and devices still faces the problem of haptic feedback. The development of the 5-axis digitizing partially solved this issue providing spatial referencing. The use of open source hardware can improve on these solutions by adding for example, visual or haptic reactions triggered from digital data.

The popularization of alternative input devices and microcontrollers eventually made possible this type of research again to a broader public, creating interesting projects as the aforementioned investigations. Despite the latest advancements, there is still room for improvement and new applications, as we particularly see it, regarding collaboration between digital processes and hand-controlled procedures. These procedures demand a new consciousness about fabrication process, combining traditional technique and digital ones in new hybrid ways of designing.

The expressive and aesthetic possibilities combined with machinic procedures and precise hand movement can generate detailed, intricate geometries, impossible to create with an either isolated method. Last to say is, that the multifaceted possibilities of digital methods need to be further explored. On the other hand, these developments, especially concerning usability and aspects of spatial awareness and haptic resonance to designers, are still in their infancy. We would like to contribute with this research to a better understanding of the interrelationship of designers and digital design methods.

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Jamming Formations

Intuitive design and fabrication process through human-computer interaction

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This paper examines the potential of User Interfaces (UI) and sensor feedback to develop an intuitive design and fabrication process utilizing granular jamming. By taking advantage of the variable stiffness of granular jamming over time, an adaptive fabrication process is presented in which various structures are formed from individual jammed components which can weave or interlock in an overall system. A User Interface (UI) is developed as a design tool which would enable interactive design decisions and operations, based on pre-designed formal and tectonic strategies. The project has four research trajectories that are developed in parallel: (1) material system research; (2) development of an ad hoc digital recording system; (3) creation of a computational library that stores users` iterations; and (4) development of a User Interface (UI) that enables users' interaction with the computational library.

Keywords: *Granular Jamming, Human-computer Interaction, Adaptive Fabrication*

INTRODUCTION

While significant progress has been made on simulation technologies, such as finite element analysis, there are still material processes which are difficult to digitally represent, simulate and predict, such as granular and fibrous materials (Daviet 2016). In the past, materials with more complex behaviors than traditional engineering materials were intuitively used by pre-industrial craftsmen, who learned how to work with them through trial and error (Carpo 2017). Craftsmen had to take the complexity of matter into account because the available materials were heterogeneous (DeLanda 2001). Through direct interaction with them, humans evolved a heightened ability to sense and manipulate the physical world (Ishii et al. 2012), which led them to develop a strong connection with the nature of matter and behavior of material systems (Alexander 1999).

Today, human ability to intuitively manipulate materials can be enhanced by computational powers of iteration and intelligence, suggesting a new model of design and construction where "humans, devices

Figure 1
Assembly process for wall prototype using granular jamming.

and their shared environments might coexist in a mutually constructive relationship" (Haque 2007). Through digital recording of artistic processes and outcomes, a computational process might "learn" from human's inherent intuition with materials, and their fine motor control and cognitive abilities (Lafreniere et al. 2016). At the same time, a designer might benefit from the computational ability to calculate or generate infinite variations with speed. This bi-directional and reciprocal learning process, where the human learns from the computer, and vice versa, can lead to an understanding of how we can work iteratively between digital and physical tools and environments towards new materialities. The use of such workflow can result to the generation of unexpected designs, which may not have been able to be conceptualized or represented with a purely digital, or purely physical workflow alone.

To investigate these potentials, this research focuses on the development of an intuitive design and fabrication process for granular jamming, a material system with very complex, unpredictable and emergent behavior (Herman 2013), using a set of processes and tools for Human-computer Interaction (HCI). Jammed, discrete elements which are formed intuitively by hand are digitally analyzed, recorded and stored in a computational library.

BACKGROUND

Granular Jamming

Granular jamming is the physical process by which particles can transition between a liquid-like and a solid-like material state (Steltz et al. 2009). When the free volume between the particles is large enough to allow mobility (Jaeger 2015), the object feels soft and malleable. In this project, stiffness is achieved by applying vacuum into the membrane that contains the particles. The ability to switch between soft and rigid material states enables novel interactions for organic shape-changing interfaces and haptic feedback (Ou et al. 2013). An example is the ShapePhone by Tangible Media at MIT (2012), a mobile device that can be formed into different jammed shapes, which can transform from a phone to a watch, or a game controller (Follmer et al. 2012). Granular jamming is also broadly used in soft robotics and grippers because it enables soft robots to safely collaborate and interact with users. The Universal Robot Gripper by Cornell University (2012) is a single mass of granular material that can be pressed onto an object, conform to its shape and when vacuum is applied it shrinks, hardens and grips it (Amend et al. 2012). An effort to bring granular jamming to an architectural scale was conducted by Lucy McRae and Skylar Tibbits (2015). Their project Jamming Bodies demonstrates the ability of granular jamming to change states from solid to liquid and maintain shape in large scale (Tibbits 2015). However, the result exposes the design limitations of the system when working with large scale volumetric elements that do not allow big deformations.

Human-computer Interaction (HCI) in Design and Fabrication

Human-computer Interaction (HCI) has been a fundamental element of Computer-aided Design (CAD) technologies since its foundations in the 1960s. In CAD, computer systems are used to assist designers and increase their productivity. One of the first examples is the Sketchpad, a system that uses line drawings to enable human-computer communication (Sutherland 1964). However, only recently computers achieved the goals that were set in the past, of augmenting the design process, instead of just executing mechanical and accounting tasks (Negroponte 1975). Today, with the use of User Interfaces (UI), the communication between humans and computers becomes intuitive and fast, enabling their direct collaboration in design decision making. The project Making Gestures explores the possibilities of design and fabrication through real-time HCI by using body gestures to establish a dialogue between the human and the fabrication machine (Pinochet 2015). In a different way, in the project HIVE human-robot collaboration is achieved through a wearable interface that provides fabrication and assembly instructions to non-expert users, enabling them to participate in the production and construction of a robotically fabricated structure (Vasey et al. 2016).

Research Aims

This research aims to investigate new protocols for interacting and designing with granular jamming using principals from HCI, in order to enhance the ability to design intuitively with a material system which is extremely difficult to simulate and predict. The ability of granular jamming to switch between soft and rigid material states allows an intuitive forming process and provides the possibility of generating various designs. This variability of designs coupled with sensing technology enables the recording and processing of multiple design iterations. The recorded information is stored in a computational library through a UI (Figure 2). The integration of material and software leads to a highly adaptable and open-ended construction system. This system offers easy fabrication and high variability of forms, taking advantage of both continuous and discrete design processes.

METHODS

Material System

In this research, a membrane filled with free aggregates is used for granular jamming. A series of experiments is conducted in order to determine the most performative membrane and aggregates. The criteria for choosing the materials are: (1) the ability to be formed easily and quickly by the user; (2) the stiffness transition between the soft (fluid-like) and the stiff (rigid-like) material states; (3) the ability of the system to achieve and maintain any given shape with small tolerance; (4) the ability to be sealed and remain stiff after stopping applying vacuum to the membrane; and (5) the sustainability and recyclability of the materials.

Thermoplastic materials such as Polypropylene (PP), High-density Polyethylene (HDPE), Ethylene Tetrafluoroethylene (ETFE) and Polyvinyl Chloride

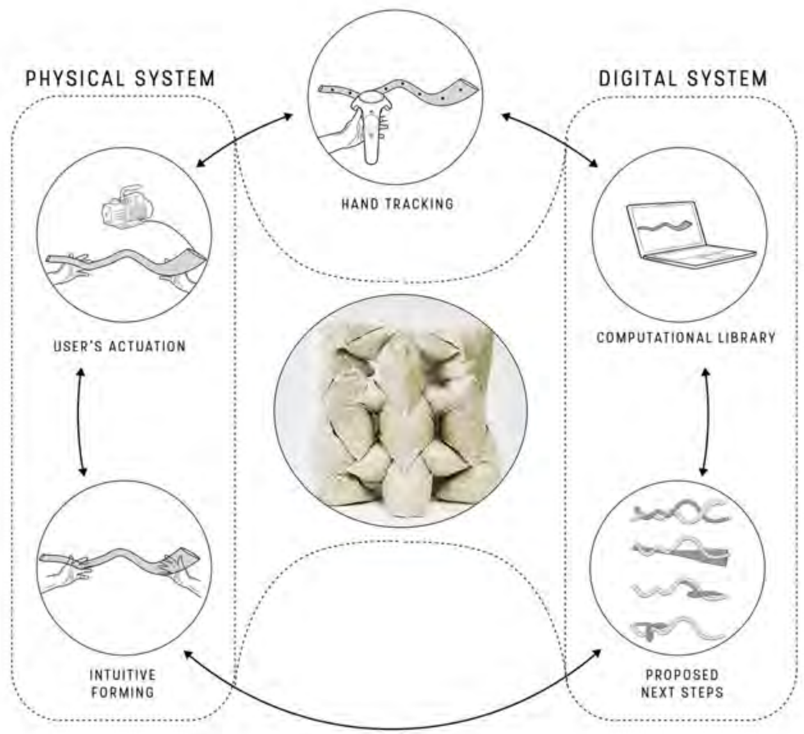


Figure 2
Design and fabrication process

(PVC), as well as rubber-like materials, such as Latex, are tested for their capacity to act as an outer membrane.

Latex achieves the largest range from soft to stiff material states, with the capability of becoming a stiff and stable structure. However, because Latex is not a thermoplastic material it is difficult to seal and thus requires a constant vacuum to maintain a stiff state. Among the thermoplastic materials, the most performative is the PP vacuum membrane, because it can be easily sealed avoiding any leaks and it can maintain its shape after forming. PP has the additional ecological benefit of recyclability.

Aggregates play a critical role in the performance of granular jamming because their material properties influence the degree of stiffness and stability that the system can achieve. Aggregates of different shapes, sizes and textures are tested, such as salt, wood shavings, straw and wood sticks. The most effective material in terms of strength, weight and formal stability are the wood shavings. The small size and the rough edges of the wood shavings provide big contact area among the aggregates which leads to stiff results. The lightweight properties of wood shavings allow users to easily form large components and the system to be scaled up and create bigger

Figure 3
Family of components: (A) rectangular, (B) linear, (C) “Y” shape, (D) “H” shape and (E) “U” shape.

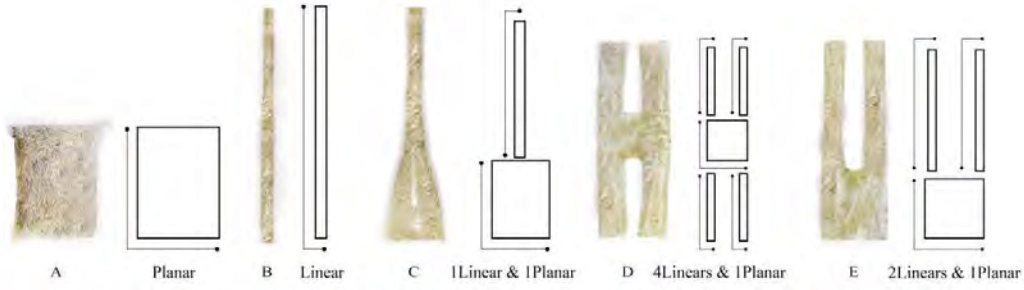
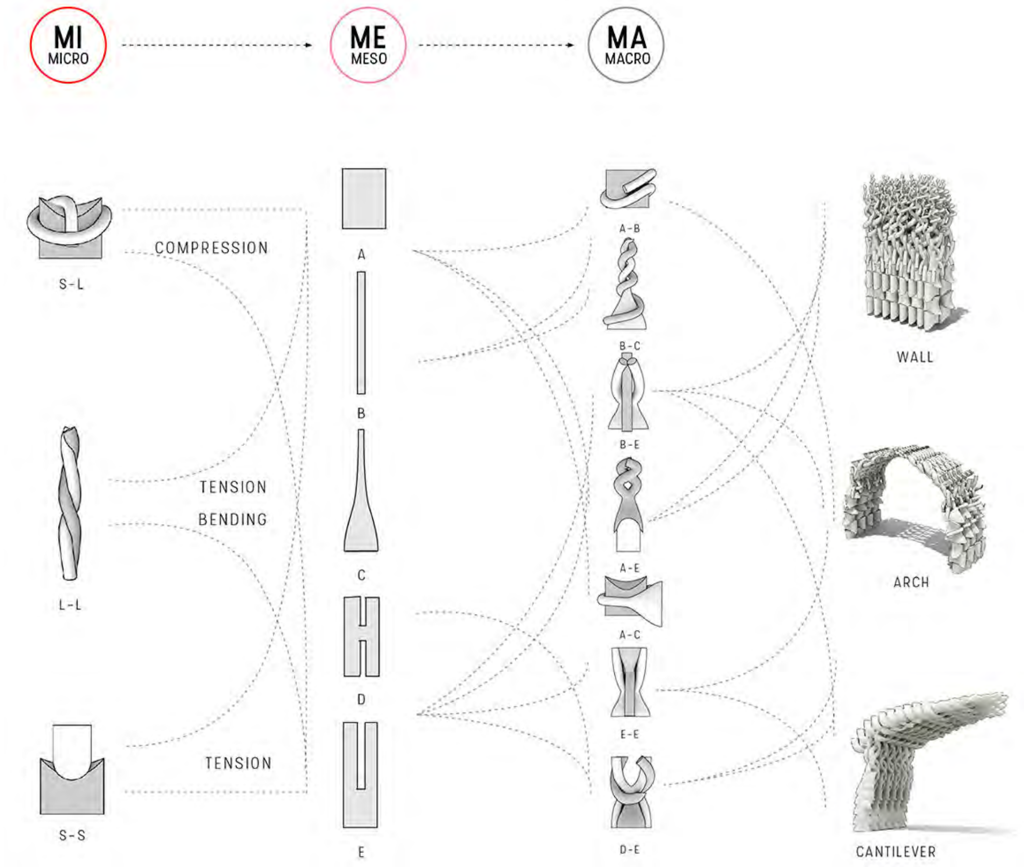


Figure 4
Interscalar design strategy for micro, meso and macro scale



can be found as a byproduct.

Thus, the material system consists of a Polypropylene vacuum membrane filled with wood shavings. Four main processes need to take place for the fabrication of the system: (1) cutting the membrane into the desired shape using a knife or cut plotter; (2) sealing the edges of the cut membrane with a flat iron to form a cushion; (3) filling the membrane with aggregates; and (4) sealing the membrane after the system is vacuumed.

Design of Components

Human scale and lightweight components are designed to enable the fabrication of intuitive and fast formations. These components vary in sizes and shapes offering different performances, form variations and tectonic connections after shaping. More specifically, they consist of linear and planar parts, arranged in different configurations. The thin, linear parts of the components are light, easy to form and have many form variations. On the other hand, the wide, planar parts of the components can adapt and mold in any shape and provide very stiff results. Although this family can be extended indefinitely, for the scope of this project five geometric patterns are chosen: the rectangular, the linear, the "Y," the "H" and the "U" shapes. These components create a tectonic system for granular jamming and showcase the variety of designs and performances that can be achieved (Figure 3).

Interscalar Design Strategy

An interscalar design strategy for granular jamming is developed to assemble the components into larger structures (Figure 4). This strategy is not a fixed design proposal, but rather an open system that keeps being developed when more users utilize it. The design system runs at different scales, starting from the micro scale of the connections between components, going to the meso scale of forming typologies and the macro scale of assembly techniques.

Adaptive Connections. In the local scale, three types of connections are developed based on the properties of the material system. These connections depend on the size of the connected parts and can be divided in these categories: (1) thin-with-wide part, the wide part acts as a mold for the thin one, surrounds it and locks it in place; (2) wide-with-wide part, the two parts mold into each other; and (3) thin-with-thin part, the parts are intertwined and interlock with themselves (Figure 5).

Figure 5
Physical prototypes of adaptive connections: (A) thin-with-wide part, (B) wide-with-wide part and (C) thin-with-thin part

Forming Typologies. The malleable components can be formed and assembled in three ways: (1) a one-dimensional linear assembly; (2) a two-dimensional planar assembly; and (3) a three-dimensional volumetric assembly. In the meso scale, the investigation focuses on how these typologies can form linear, planar and spatial structures (Figure 6). These forming typologies indicate the growing behavior of the structures and imply global design possibilities.

Assembly Techniques. Three assembly techniques are implemented, by combining the forming typologies in various manners. The first technique is weaving, which consists of linear and volumetric elements and has a horizontal growth logic. Each volumetric element is interlocked with its neighboring one while the horizontal linear elements run through them (Figure 7A). The second technique is interlocking, which consists of planar and volumetric components that lock themselves in all directions. The fabrication process follows a bottom to top sequence (Figure 7B). The third technique is intertwining, which combines linear and planar elements and has a vertical development. This technique requires that linear elements are intertwined with themselves and then planar elements bring them together by forming loops around them (Figure 7C).

Figure 6
Physical prototypes of forming typologies: (A) one dimensional linear assembly, (B) two dimensional planar assembly and (C) three dimensional volumetric assembly.

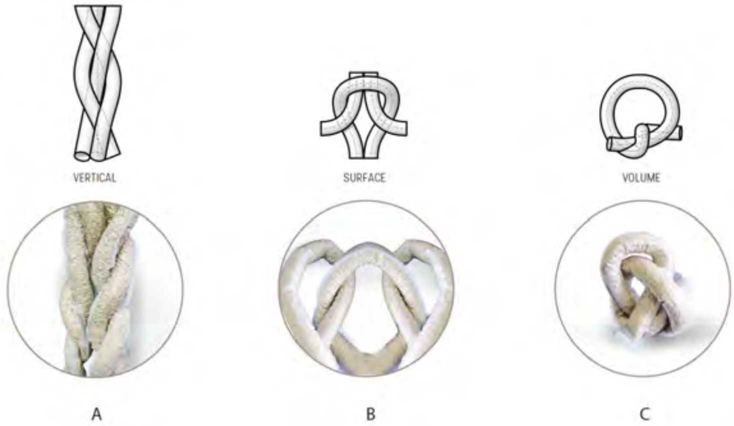
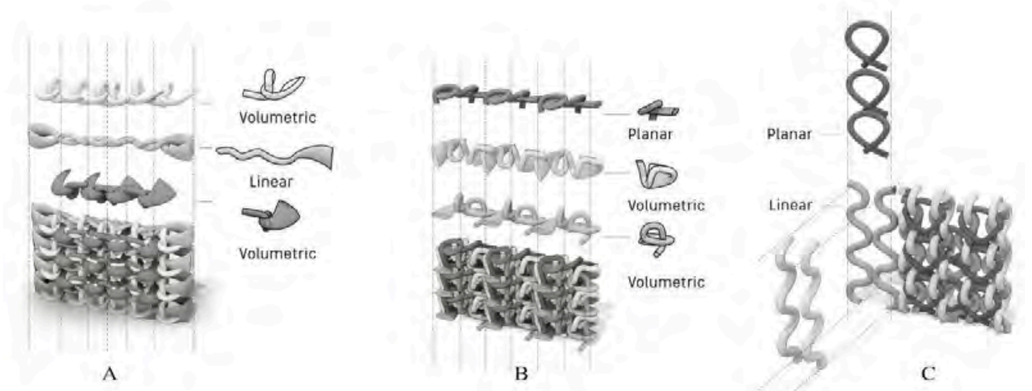


Figure 7
Digital models of assembly techniques: (A) Weaving, (B) Interlocking and (C) Intertwining.



Bending and Compression Tests

Various components and connections behave differently under specific structural loads. A series of structural tests are conducted to explore the possibility of creating larger structures with granular jamming. Each connection type is tested under specific loads, according to their expected best performance in bending and compression. A linear component and a thin-with-thin connection are tested in bending, while a rectangular component and a wide-with-wide connection are tested in compression (Figure 8).

For the three-point bend test, specimens of 30 cm x 10 cm x 2 cm are prepared and the maximum load is 60 N. For the compression tests, the specimens' size is10 cm x 10 cm x 6 cm, reaching a maximum load of 10.000 N. In all of these tests, there is a fast and large deformation of the components. However, because of the elasticity of the membrane, the material system does not fail through ripping.

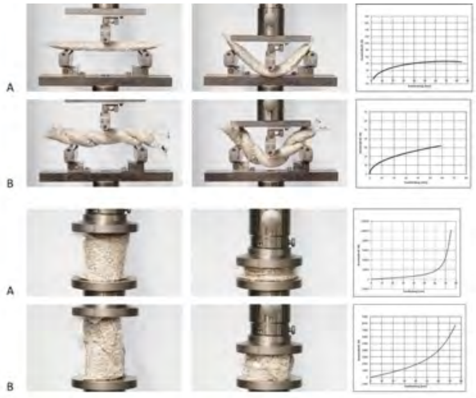


Figure 8
Bending tests: (A) linear component, (B) thin-with-with connection. Compression tests. (A) volumetric component, (B) wide-with-wide connection

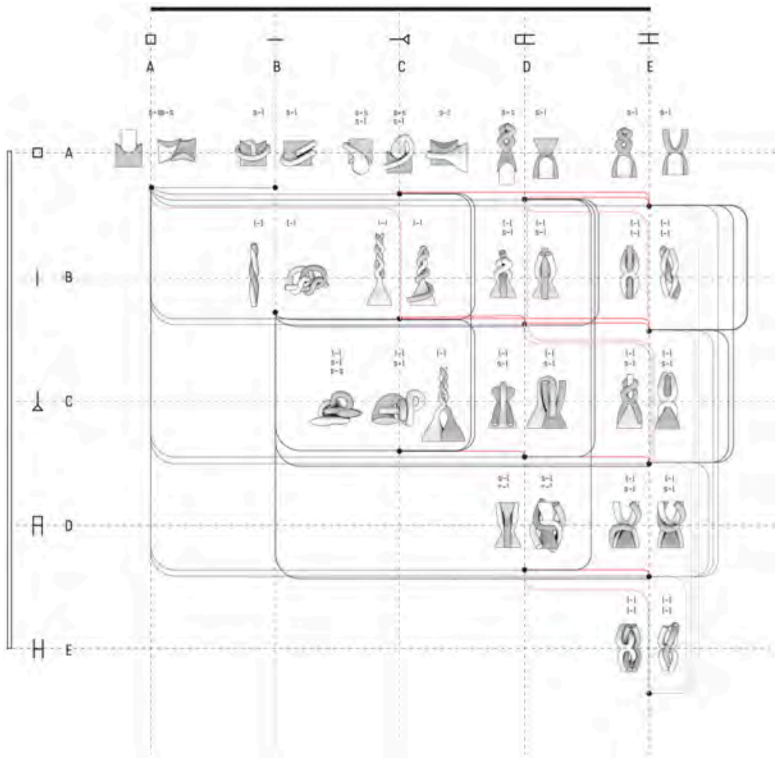


Figure 9
Matrix of all possible aggregations

Global Design Possibilities

The results from bending and compression tests and our design strategies are compiled into a matrix to showcase all possible aggregations and connections within these variables (Figure 9). This matrix is used for a series of digital and physical models that examine the potential of the system to create various structures with different architectural and structural qualities. These typology studies include a wall, an arch, a cantilever (Figure 10) and they also examine the possibility of these typologies to adapt to an existing context. For these typologies, volumetric rectangular components are placed at the bottom with wide-to-wide connection because of their compression strength. On top of them, the "H," "Y," or "U" shape components are used because they are able to take bending moments and make a transition to the linear components which are placed on top. Linear components are placed on top because they are the lightest and can create a gradient of porosity. In cases in which the overall form of the structure creates high tension, such as in the cantilever, linear elements are tightly intertwined. Finally, granular jamming allows the structures to adapt to different existing environments and boundary conditions. The linear parts of the components are easily attached to existing elements, while the volumetric ones are molded on uneven terrains.

Prototypes

Two medium-scale prototypes are developed to showcase the various design potentials of the system. The first prototype is a vertical wall (Figure 11A). The design is simple since only the rectangular block component is used. The components are molded sequentially into each other, using wide-with-wide connections. The size of the blocks is 0.40 m x 0.60 m x 0.20 m, while the total size of the model is 1.00 m width x 0.40 m depth x 1.20 m tall. This structure shows the structural potential of the system and its ability to quickly construct large structures with adaptive bricks.

The second prototype is an adaptive structure that grows into an existing frame (Figure 11B). The dimensions are 1.00 m width x 0.80 m depth x 1.60 m height. The used components have a maximum length of 1.50 m and 0.40 m width, which allows them to be easily formed by the user. All the five types of components are used and they are connected in various ways with each other. The structure adapts and molds on the top part of the frame.

Figure 10
Physical prototypes of (A) an adaptive arch, (B) an adaptive wall

Figure 11
Final prototypes; a vertical wall (A) and an adaptive free form structure (B)

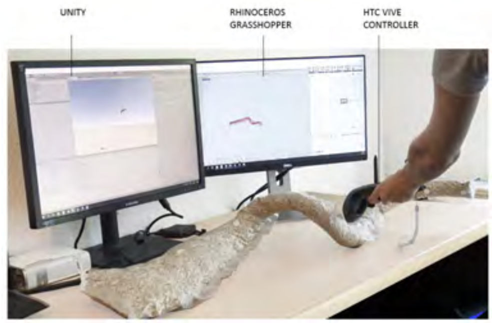


Figure 12
Physical setup for digital recording

Digital Recording

The previous design studies verified that granular jamming offers a vast amount of design possibilities because it takes advantage of both the malleable characteristics of a continuous system and the combinatorial characteristics of a discrete system. Thus, it produces a very large amount of design iterations by forming and assembling the components in different ways. By recording and storing the iterations that multiple users produce, an expanding computational library is created.

A digital recording system is developed to record every unique piece formed by the user. An HTC VIVE is used to track the user's hand when moving along the piece and encode this information from the physical to the digital environment. Although there are many recording systems that can be used, such as machine vision and positioning systems, the HTC VIVE handset is preferred because it is very easy to use, it is accurate and fast.

The components are marked with key-points on their boundaries. The user has to hold the handset and follow the piece that was just formed, pressing the handset button in every key-point. The recording happens in real-time, digitizing the position of the predefined key-points from the physical environment to Unity - the game engine platform that is compatible with HTC VIVE-. From Unity, the position of the points is transferred to the Grasshopper interface - the parametric plugin of Rhinoceros 3D modelling software - through the User Datagram Protocol (UDP) (Figure 12). These points are used by a custom computational tool to create an abstract digital model of the physical component. This tool is developed in Grasshopper using a shape matching goal algorithm. This tool requires the form of the initial unformed component as an input, imported as a mesh, and the key points of this component imported as 3d points. After receiving the new key-points from the HTC VIVE tracking method, the tool matches the initial points to the recorded ones. This process results in a digital geometrical approximation of the physical formed component.

Computational Library

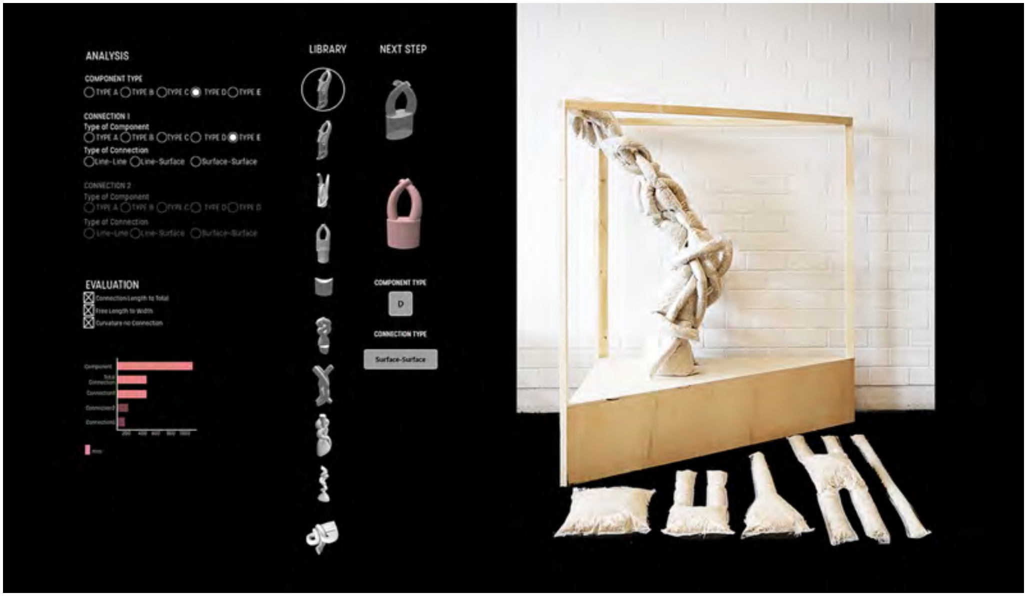
After each digital recording, the computational library analyzes, evaluates and stores the geometry of each component that is produced (Figure 13). When the recorded mesh is saved, the library runs an analysis, in which the geometry is examined according to the interscalar approach that was described before. The code identifies the location of the component in the structure at a global level, the type of component (rectangular, linear, "Y," ,"H" or "U" shape) at a meso level, and finally the types of connections (thin-with-wide, thin-with-thin, wide-with-wide) at a local scale.

The data gathered from the analysis is used to evaluate the components that are produced. There are three criteria that each iteration should ideally fulfil in order to be stored in the library: (1) the ratio of connection area with other components to the total area of the component; (2) the type of the component in relation to the structural needs of the structure at that area ; and (3) the type of connection in relation to the structural needs of the structure at that area. If these criteria are fulfilled then the iteration is stored in the library. The information that is stored in the library is the mesh geometry and all the data produced during the analysis and evaluation describing the component from global to local scale.

Development of a User Interface (UI)

A User Interface (UI) is developed which enables intuitive interaction with a computational library. Through this interface, the data that is collected from previous iterations becomes accessible to the current users. More specifically, the interface visualizes the previous design iterations and gives the user the opportunity to explore the interscalar analysis that is conducted by the computational library. In the macro scale, the user defines the typology of the structure that wants to be built, for example, a wall or an arch. The interface visualizes all the previous structures of this typology that were built before and analyzes what types of components and connections were used. According to this data, the user is free to follow some of the previous designs or to experiment with new designs that will further expand the computational library. The interface was developed entirely in Grasshopper, using the Human UI plug-in.

Figure 13
Structure of the computational library



RESULTS AND REFLECTION

The research succeeds in developing an intuitive design and construction process for granular jamming, utilizing data collection methods. Two medium-scale prototypes are fabricated, showcasing the design potentials of the material system. These structures are intuitively and rapidly fabricated while remaining low-cost and recyclable. A tracking system is developed to digitize the human creations into the digital system, as well as a computational library which is able to store these designs, and then compare and analyze them. Finally, a User Interface (UI) is developed to facilitate interaction with the background computational library during fabrication.

Regarding the material system, leaks that are caused either from inefficient sealing or tearing of the membrane damage the jammed components. In this case, although the aggregates can be reused, the membrane has to be replaced. An interesting aspect of the material system that is out of the scope of this research, is its potential reversibility. By embedding non-leaking valves on the membranes, the components could be removed, reshaped and reused at any time.

In terms of the digital recording system, the geometry generation tool is created specifically for the five components that are used. A more generalizable tool could be further developed for the simulation of more complex component geometries. Moreover, for faster and more efficient interface visualization, other programming languages such as Visual Basic or Java should be considered.

Finally, an aspect which is outside of the realm of this project is to test the success of the User Interface (UI) in transferring knowledge to users unfamiliar with the material system and fabrication process. Further research could also investigate the integration of more advanced methods of data analysis. Machine learning and artificial intelligence based on observation of the physical world can lead to an advanced bi-directional learning process between the human and the computer. Generative design tools could be implemented to suggest new unexpected designs to the users based on the data gathered from previous design iterations.

CONCLUSION

This study provides a proof of concept for an HCI system that enables new ways of intuitive design and construction with granular jamming. The broader vision of this project is to enhance architects' ability to work intuitively with unpredictable material, where intuition is not only understood as a single user's material intuition shaped by singular experiences. The recording of multiple users' experiences might enable knowledge and intuition to be crowdsourced, digitally stored, processed, and subsequently transferred. Accessibility and crowdsourcing in design processes can allow a dynamic pool of unspecified users (Lasecki et al. 2011) to contribute design iterations to a computational database. This leads to an acceleration of democratization of knowledge and craft to anyone willing to teach and learn (Lafreniere et al. 2016).

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SEEstem

Wearable navigation device for people with visual impairments

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Visually impaired people represent a large amount of the Brazilian population. However, although a wide range of existing legislation ensures accessibility, most of the Brazilian public spaces are inadequate to accommodate disabled citizens. In this context, this paper presents a digital device, which combines the smartphone technologies with Arduino microcontrollers, for orientation and obstacle detection. We tested the minimum viable product and the first vest prototype through a user-centered usability test, which combines HCI assessments to other techniques, such as semi-structured interviews. As known, these wearable devices and mobile applications are in the center of the Internet of Things discussion. This study is expected to be an alternative for the urban mobility of visually impaired people, allowing them to have a more active and independent behavior in public spaces.

Keywords: *Assistive wearable devices, Visually impaired people, Accessibility, Human-computer interaction, Collaborative design.*

INTRODUCTION

According to the Brazilian Institute of Geography and Statistics (IBGE, 2011), almost 35 million people declared a type of visual deficiency in Brazil. Visual impairment reduces the ability to identify certain environmental attributes, such as colors, sizes, distances, shapes, and positions, which affect their mobility and interaction in space. To overcome the vision loss, the visually impaired person uses the remainder of the sensory system, to obtain the information for orientation and mobility (Dischingher, 2006).

It is clear that the visually impaired represent a large amount of the Brazilian population, which should have the same access and opportunities as other citizens. However, although a wide range of existing legislation ensures accessibility, most of the Brazilian public spaces are inadequate to accommodate disabled citizens. In the country, 42.6% of the municipalities do not present any accessibility items for people with disabilities (IBGE, 2011). Thus, the absence of resources establishes physical and informational barriers, which culminates in their seclusion at home, preventing them from navigating in public spaces.

In this context, this work aims to bring alternatives to fill the lack of adequate infrastructure of the Brazilian public spaces, related to the visually impaired accessibility. The emergence of new digital technologies has brought several possibilities in Architecture and Urbanism, not only for the technological innovation itself, but for making changes in its uses, modes of production, design and manufacture. It is understood that digital technologies are able to reconfigure the navigation in urban spaces, through smaller (miniaturization) and low-cost mobile devices. The development led to the integration of technologies into everyday life, making them more ubiquitous. Therefore, by admitting the hybrid character of spaces, this paper aims to present a digital device development which combines the mobile application with Arduino microcontrollers and sensors, in order to add new layers of information and improve the accessibility of urban spaces for visually impaired pedestrians.

According to Velásquez (2010), there is a variety of Electronic Mobility Aids available to assist visually impaired people, besides traditional resources, such as a cane and a guide dog. Most of the systems are mobile or wearable devices, which allow the user to manipulate the interface and perform another activity while moving through public spaces. These resources can combine several types of inputs and outputs, which provide information about the outdoor environment and warn the user about obstacles.

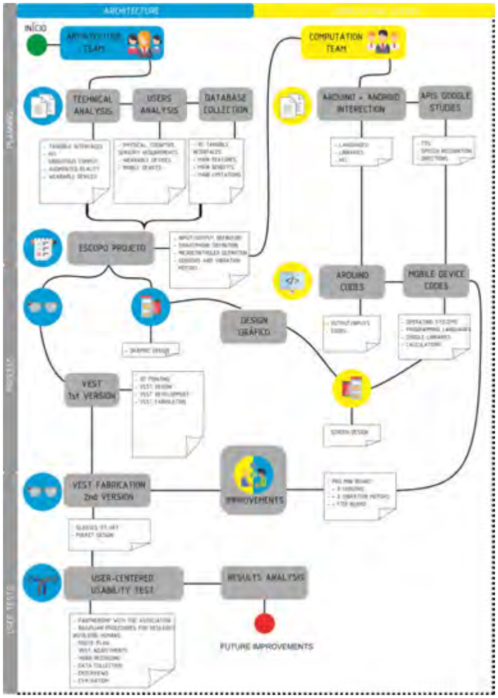
However, this variety of mobility aids for the visually impaired people does not correspond to the relatively low users' adherence rate. Some researchers believe that the costs, weight, ergonomic problems, and the absence of several functions in the same device are the possible reasons for this lack of acceptance by visually impaired people. Even smartphones have built-in accessibility features and integration with the Google APIs, some of these technologies still have some limitations, such as the inaccuracy of the sensors and a lack of versatility related to the number of sensors and their positions. In this sense, this work incorporates additional resources to mobile devices, through Arduino type microcontrollers, which aims to combine the smartphones technologies for orientation and obstacle detection.

METHODS

The design of the device involves several challenges, from technological requirements to physical, cognitive and sensory demands related to visually impaired people navigation in urban space. Due to these peculiarities, the interface is a result of a teamwork in a collaborative design process that joined together researchers from the Architecture and Urbanism Department and the Computer Science Department at the Federal University of Viçosa, in Brazil. This multidisciplinary group involves professors and researchers from Nó.Lab (Digital Modeling Lab, related to the Architecture and Urbanism Department) and researchers from LABD2M (Mobile Devices Development Laboratory, based at the Computer Science Department).

The architecture researchers were responsible for the first survey and database collection of tangible user interfaces, the wearable device design and development as well as the definition and application of a user-centered usability test. The computer scientist researchers were responsible for the application development and the Arduino microcontroller integration. However, the group discussed together the schedule, the main activities, and articulated the actions for improving the results in each stage. This multidisciplinary work allows the comprehension and integration of several areas of knowledge, making possible the development of more effective and pleasant interactive systems. The Figure 1 illustrates the workflow activities and teamwork.

Figure 1
The workflow activities and teamwork



The research is based in five stages:

(A) A survey and database collection of 85 tangible user interfaces related to visually impaired people to analyze and understand their main features, functions, benefits and limitations concerned with user's interaction.

(B) Main Hardware and software components: The device was natively developed for both platforms (Android and iOS operating systems) , which corresponded to 99.7% of the global mobile market in 2016 (GARTNER, 2016). For Android, the application was developed in the integrated development environment (IDE) Android SDK and Android Studio, based on Java and Kotlin programming languages, and the visual interface in the XML language. The iOS operating system uses the Swift language, the visual interface in the XIB language and it was developed in the Xcode integrated development environment (IDE). The minimum mobile requirements for Android operating system is 4.4 KitKat version and 32 Gb of storage, while the iOS operating system needs a 9 version and 32 Gb of storage. Additionally, the mobile device also has internet access with the data packet, GPS, microphone, and it can be connected to a headset.

The minimum viable product (MVP) input consists of speech recognition, using Speech Recognizer, in which the user requests a navigation route. The request is transformed into a json format file, converted to a synthesized speech output, developed from the Text to Speech (tts), both libraries maintained by Google. It also needs the Google APIs, such as Google Maps, Google Directions, Google Locations, and Google Places, for receiving navigation information in outdoor public spaces. All of them are the implemented solutions which allow the users to arrive at their destination, informing them when they are within a reasonable distance, the direction (left / right) and angulation of 45 °, 90 °, or 180 °, from a "critical point".

(C) Obstacle detection and Arduino microcontroller integration: This stage includes the Arduino microcontroller for obstacle detection through ultrasonic sensors (HC-SR04) and a programming language derived from C / C ++. The ultrasonic sensor transmits the position and the obstacle distance, which activates the vibration motors (1027). The Arduino board is the PRO MINI model (ATMega328), a compact format (33x18x3mm and 3g) and low-cost board, with 32KB memory. The microcontroller has a crystal oscillator of 16MHz, USB connection, reset button, 14 pins of digital input / output, 8 pins of analog inputs (for sensors with variable values), and 6 pins with PWM outputs (for sensors connection). The board can be powered by the USB connection or by an external power supply through the Jack connector. We defined the use of 7 ultrasonic sensors (HC-SR04), which detect objects between 2 cm and 4 meters, with a 3 mm precision, and 7 vibration motors (1027) for tactile feedback (Figure 2). In addition, we used the FTDI FT232RL card, which allows the connection of TTL devices to USB.

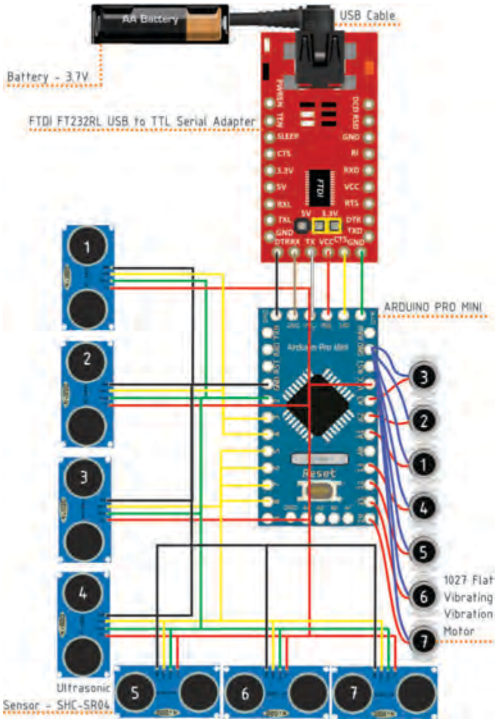


Figure 2
The Arduino board, the ultrasonic sensors and vibration motors.

(D) Wearable device development: The vest and the glasses integrate Arduino sensors to assist in obstacle avoidance. There are one Arduino board, five ultrasonic sensors, five vibration motors, connectors, cables, and a power source. The visually impaired person will hardly abandon the cane since it complements the digital device. Therefore, below the waist, the body will be "protected" by the use of the cane, thus the sensors are concentrated in the waist, abdomen and head region.

The vest has four front pockets: the front pocket has an ultrasonic sensor hidden by the cloth. The pockets are attached to the vest by removable Velcro strips, so it is possible to wash the cloth without damaging the components. On the head, the users wear glasses with the ultrasonic sensor and a headset with wireless microphone, joined through 3D printing components, in thermoplastic material. These placements were strategic as they allowed stability for obstacle detection, since there is a natural tendency to keep our head aligned. A 3D printing frame attached to the glasses allow the ultrasonic sensor positions.

For the smartphone location, the researchers proposed an arm phone holder, similar to a sports armband case, in order to keep the user's hands-free for handling the cane. The movements of the arms do not disturb the device operation and its position does not interfere with the sensors' magnetic field. The data transfer between the Arduino microcontroller and the smartphone occurs via USB cable, which can also be used for power charging.

The vest design consists in two stages: the first one in raw cotton fabric, replaced by a second design in gabardine fabric, as well Velcro zipper. The researchers also used some basic sewing tools (sewing machine, thread, needle, etc.).

(E) The user-centered usability test: the tests combined Human-Computer Interaction (HCI) methods for the design and evaluation of user interfaces (UIs), with semi-structured interviews, in a partnership with the Association for the Blind and Visually Impaired people in Juiz de Fora, a Brazilian city. The interface evaluation involved students who take a class for improving the mobility and guidance through digital technologies, at the same partner institution. The researchers planned a walking route nearby the partner institution in Juiz de Fora (on Avenida dos Andradas), observed them and recorded their actions through video recording. The research follows the Brazilian standards and procedures for research involving human subjects and has the ethics committee certificate of approval.

RESULTS

The minimum viable product (MVP)

This paper shows the minimum viable product (MVP), a product with the basic and essential functionalities, in order to validate its usability and provide feedback for future improvements. As the first steps, the researchers created a wire frame tool, which outlines the main structure of the information flows and visual screens in the mobile application. The interface has three main modules: (1) Information module: describes the direction and angulation that the user should follow; (2) Location module: the user's current position in space and (3) Obstacles Module: distance alert and position of obstacles. The application input consists of speech recognition, using Speech Recognizer, in which the user requests a navigation route.

The Obstacle detection and Arduino microcontroller integration consists of three ultrasonic sensors and three vibration motors. Four pins connect the sensors to the Arduino board: the Vcc, Trigger, Echo and Gnd. The VCC and GND pins are responsible to power the sensor, connecting to the Arduino VCC and GND pins, respectively. The TRIGGER and ECHO pins trigger the ultrasonic signal, and measure the time it returns to the sensor, connecting to the digital pins as input d (pins 3 - 9) and output (pin 2), respectively (Figure 2). After being connected to the board, the sensor starts the scanning by calculating the distance between the object and the user, provided by the ultrasonic library, which reads, transmits data from the sensor and assigns the variables cmMsec and inMsec values of distances.

The formula "D = PNA * 340/2" calculates the distance, where "D" is the distance; "PNA" the pulse at high level; "340 m / s" the ideal speed of sound; and it is divided by 2, which is the time the sound waves take to go back to the sensor. If the program detects an object at a risky distance to the users, the digital outputs activates the vibration motor, alerting them to the obstacle.

For the wearing device, according to Seymor (2008), wearable computing should prevail for its functionality, as much for its comfort and aesthetics. To this end, the visually impaired person should dress the vest in a versatile way, placing the technology to different locations in the body for detecting the obstacles. Additionally, as the person with visual impairment will hardly abandon the cane, the device will complement its use with sensors in the waist, abdomen and head region (Figure 3). The pockets located on the vest have two different parts: The front one, where the ultrasonic sensors are located, partially hidden, and the back of the pocket, where there is a vibration engine in order to be in more contact with the skin, so the user can feel the vibration warnings. The pockets are attached to the dressing by a removable Velcro system, so it is possible to wash the cloth without damaging the components. Additionally, as the vest should not cause discomfort or limit their daily actions (sit, run, walk, among others), there is a front zipper, which allows the user to open or close the vest. The smartphone is held through a similar sports armband case, which keeps the user's hands-free for handling the cane.

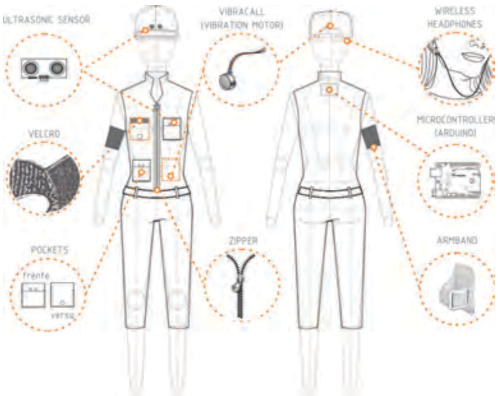


Figure 3
The vest design (first proposal)

The vest's prototype manufacturing faced some challenges. At the beginning, the wearing device consisted of a vest and a pair of glasses, but the researchers replaced the last one by a hat in order to hide the wires (the electrical circuits, Figure 4). In addition, the more sensors and motors, the more wires are required to connect them in order to activate their settings, which also compromises the aesthetics, since the final volume of wires was higher than initially planned (Figure 5).

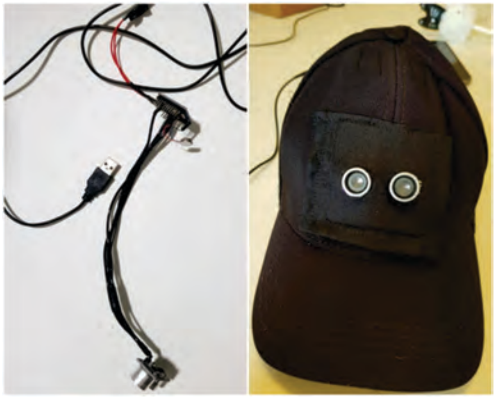


Figure 4
The pair of glasses replaced by a hat, in order to hide the wires.

Figure 5
The vest and the final volume of wires, higher than initially planned

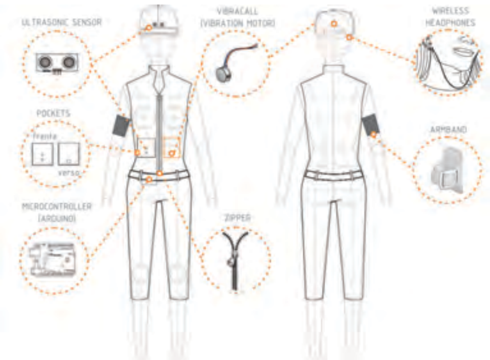


Figure 6
The vest design after some tests (second proposal)

After some tests, the researchers decided to use just a pair of sensors and motors (Figure 6), only in two pockets, due to their position and proximity. The sensor readings in the abdomen are the same of others located in the waist, in such a way that one of them is dispensable. Moreover, some tests showed that more sensors and motors would read the user's own body as a barrier (for example, the arms movement), causing an obstacle avoidance false reading. As a result, we also adjusted the Velcro positions.

The pocket design also changed. Initially the Velcro was intended to connect the pocket with the vest and be removable. However, due to the final Arduino kit volume (board, sensors and jumpers), it would be more feasible to place all the sensors inside the vest. This solution prevents the volume from not compromising the aesthetics and also not bringing discomfort for some users. In order to facilitate washing the cloth, the liner does not have seam in its lower bar, allowing detaching it from the vest. We also observed the fragility and the need to reinforce the vibration motors welding, as there were some rupture during their installation in the vest. However, such issues could be easily repaired, and they do not compromise the cloth manufacture.

The user-centered usability test

As the device integrates mobile and wearable technologies, as well as tactile and auditory feedbacks, which makes the interaction much more complex, the researchers combined HCI assessments to other techniques to evaluate the wearable, some of them from Ashbrook et.al (2009). For this evaluation, we performed a user-centered usability test with the students from the Association for the Blind and Visually impaired in Juiz de Fora, Brazil. We observed them and recorded their activities through video recording, along a 400-meter itinerary, previously defined in accordance with the staff of the same institution.

The field test happened on Avenida dos Andradas, in Juiz de Fora - MG, which is the starting point at the "Association of Blind People of Juiz de Fora", and Nossa Senhora da Glória Church as a destination, on the same avenue. This is also a usual route for its students, which could promote greater safety for them while testing the device, as well as the possibility of checking the counterpoints without major challenges.

The institution chose three volunteers to partici-

Figure 7
User 1 map - first route (red means failures and yellow obstacle detection)

Figure 8
User 1 map - second route (red means failures and yellow obstacle detection)

Figure 9
User 2 map - first route (red means failures and yellow obstacle detection)

pate in this experiment: two blind men (a 34-year-old and a 68-year-old men) and one low vision woman (51 years old). Following the Research Ethics Committee regulations, we replaced their names by a sequence from 1 to 3 to respect the anonymity of the users throughout the entire evaluation process. The test began at 2:00 pm and surveyors completed the 400 meters in an average of 6 minutes. For a better representation of the information, we generated user-centered maps, which show the identified and unidentified obstacles, complemented by pictures. In the maps, it is possible to observe the activity of the device in the three users.

We reported different outcomes, according to the user. The first user, for example, (Figure 07 and 08) wears vest sizes bigger than the others, and the cloth adjustment in place did not provide the comfort, nor the maximum potential of the vest, since one of the sensors ended up hidden. In addition, this user walked faster than the others, and most of the time the obstacle warning occurred when the user was already very close to the obstacle.

The user number 2, (Figure 09 and 10), detected less obstacle than the others, probably as she is not completely blind (low vision), she can divert from some obstacles before she even approaches them. User number 3 map (Figure 11 and 12) is the one who presents the highest frequency of detection, such as walls and bigger obstacles. At the end, the device detected 59% obstacles, failing 41% of the time. We considered detection failure when the device did not trigger the warning in time to avoid it. Sometimes the device could not detect tiny and thin objects, such as the poles near the destination, as well as some objects below the user's waist (dumpsites), since there were no sensors in that region.

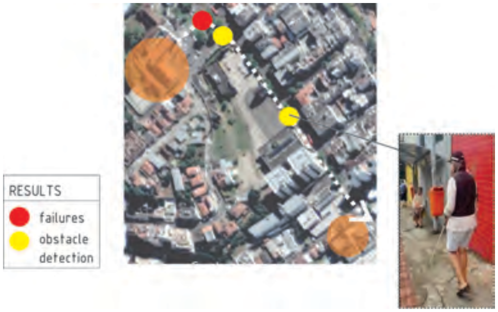


Figure 10
User 2 map - second route (red means failures and yellow obstacle detection)

Figure 11
User 3 map - first route (red means failures and yellow obstacle detection)

Figure 12
User 3 map - second route (red means failures and yellow obstacle detection)

Although the smartphone application functioned properly, it also did not show the expected result. The straight-line test detected a lack of voice instructions when there was no changing in the route, in such a way that some users considered it to be an application bug. The application should send more positioning information, in shorter periods of time, to ensure they were on the right path.

After the tests, we conducted semi-structured interviews to understand each users' experience. The user number 1 praised the initiative and felt no difficulty in the device usability. However, he pointed out some flaws, as described above, and stated the device should be improved so that he could re-use it with confidence. He stated that adding more sensors would bring discomfort to the user and suggested improving only the existing system without adding any extra item to the wearable. The second interviewee liked the device and the sensations it provides. During the conversation, she showed a superior degree of satisfaction compared to the previous interviewee and did not present many complaints about the device. However, she stated some discomfort with digital devices, and she would need to get familiar with the technology to use it again with confidence. In addition, in contrast to the first interviewee, she believes it would be interesting to add more sensors.

Finally, the third interviewee also praised the initiative and the device, even if it needs more improvements. During the interview, the user stated that he walked along the street more carefully than normal since he had never used the device before. However, despite reporting some shortcomings, the interviewee believes he would use the device again. As a final suggestion, he states that the number of sensors is ideal, and their increase could bring some degree of discomfort.

All the volunteers and staff from the Association of Blind People were concerned about the final cost of the device, emphasizing the need for an affordable value for its commercialization. They also requested for traffic light detection as a possible improvement.

DISCUSSIONS AND IMPROVEMENTS

The results show that more than two sensors compromises the aesthetics of the cloth, due to the final volume of wires, as well as increases the complexity to use the device. The design improvement and cloth remodeling advance towards the miniaturization, similar to the head module (Figure 13). The dressing will consist of an adjustable pouch/collar, where the sensors and vibration motors would be arranged in their extension, and the microcontroller and its battery would fit inside the existing pocket (Figure 14 and Figure 15). Such changes would improve the vest flexibility of use, which allows changing the positioning according to the user's needs, also solving the size adjustment problems related to body types. In addition, we will replace the ultrasonic sensor to a different type, such as a laser, to reduce the margin of error and achieve the expected accuracy.

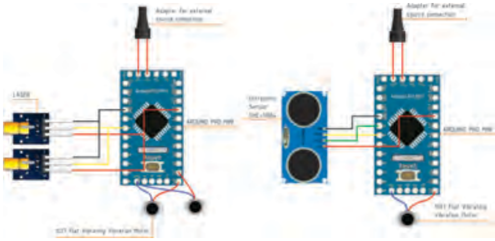


Figure 13
The pocket (left) and head modules (right), after miniaturization

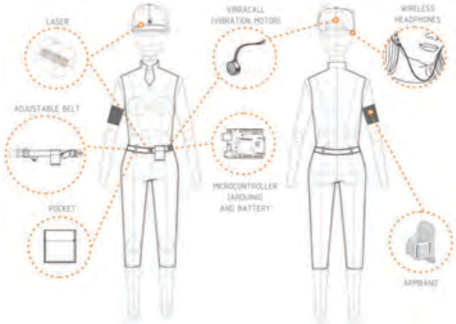


Figure 14
The design improvement and cloth remodeling: the adjustable pouch

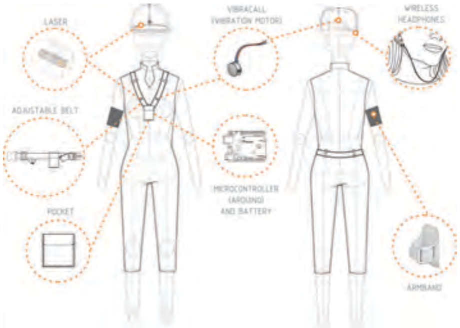


Figure 15
The design improvement and cloth remodeling: the adjustable collar

After the user-centered tests, the researchers had already made some changes to the mobile application. They migrated the Google's APIS use to Open Street Maps (OSM), which is completely free and offers some other advantages, such as pedestrian routes, and the inclusion of voluntary geographic information (VGI). Thus, the OSM enables the user to draw sidewalks and even pedestrian tracks, as well as to instruct them, even when there are no direction changes, just confirming their path from time to time, adding directions such as "go ahead", "missing" or "about 15m to the destination". We believe it will solve the problems detected during the user-centered usability test, which will improve the user's confidence on the application and allow a more reliable and safer route.

We also added a tool that allows the device to detect the traffic signals through the camera, which recognize two images: one in which the green color is evidenced, and another one in which the red color is in evidence. This generates a Gaussian or Laplacian pyramid, which only highlights what is already in evidence, obfuscating the rest. The map will emit which color has the highest amount in the camera capture, and if the result indicates the red color, the application concludes the traffic light is closed; if indicates the green color, then the semaphore is open.

As known, these wearable devices and mobile applications are in the center of the Internet of Things discussion. This study is expected to be an alternative for the urban mobility of visually impaired people, allowing them to have a more active and independent behavior in public spaces.

ACKNOWLEDGE

We thank the Cnpq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) for the undergraduate scientific initiation grant and the Graduate Program in Architecture and Urbanism at UFV (Federal University of Viçosa) for supporting this work. We extend the appreciation to the students at the Association of Blind People of Juiz de Fora, for accepting to participate and collaborate for the improvements in this work.

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Aerochair

Integrative design methodologies for lightweight carbon fiber furniture design

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Carbon fiber composites embody lightweight and strength and is a well-integrated material in various fields of engineering. In spite of its excellent material properties, it is not frequently found in architecture and design applications. In this project, the intention is to research how the material's most prominent qualities can be applied to create a lightweight furniture design. The furniture object was chosen as an example of a small architectural component with a structural capacity of holding a human body weight between 60-90 Kg. In particular, carbon fiber composites display an impressive tensile strength, and with the aim of exploring this feature, a case-study of a full-scale, hanging carbon chair was conducted. To develop a design, optimize it and realize it, an integrated design and fabrication process was developed. It combined material research, computational design, and a novel fabrication method for filament materials.

Keywords: *carbon fiber composites, computational design, lightweight furniture, chair design, fiber winding*

INTRODUCTION

Carbon fiber composites display excellent mechanical properties and have been valued within the fields of aerospace and civil engineering for decades. Even though it is not yet a widespread material in architecture and design, research done on coreless filament winding systems developed by the Institute of Computational Design (ICD) and the Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart shows how the qualities of composite filament materials can create material effective lightweight designs on an architectural scale (Prado et al. 2014).

In spite of all of its qualities, it is important to note that the package of resilience, lightweight and strength that it presents come at a cost. Carbon fiber composites are expensive compared to other material options, they are not biodegradable and are difficult to recycle. Humans working with it must wear protective gear such as masks and protective suits to avoid contact with the resin as well as the fiber strands. Even though carbon fiber is currently not considered an environmentally friendly material, the production of it consumes less energy compared to for example aluminum or steel.

In this project, the qualities of carbon fiber composites inspired the design of a lightweight piece of furniture, while its limitations motivated an effective use of the material and became the main design driver. By exploiting the materials dominant qualities to the maximum, it is possible to keep the material usage at a minimum. In the case of carbon fiber composites, their tensile strength is considerably higher than their compressive strength. This presents an opportunity to explore a design that takes full advantage of tensile forces, leading to the development of a suspended chair.

Traditional standing chairs are designed to transmit compressive forces exerted by a load of a person through the legs. Applying this design approach to carbon fiber composites could result in a dense, material costly product. By allowing the chair to hang - instead of stand - a new design expression that properly conveys the material characteristics presents itself.

To realize this concept a novel fabrication system that ensures an effective transmission of tensile forces through the shape had to be developed. Additionally, a computational tool was created in order to inform design decisions and evaluate possible outcomes.

Material System

Carbon fiber reinforced composites have been extensively employed in the military, aerospace and automobile industries due to their excellent mechanical properties such as high specific strength and stiffness. In spite of their high cost, composites are widely opted because of their tailored properties (Reddy et al. 2017).

Carbon fiber is a versatile material and can be obtained in different formats such as yarn, braids, multiaxial fabrics, non-crimped fabric or unidirectional fabric. The format used in this project, the yarn, is suited for processes like prepregging, filament winding, pultrusion, weaving and braiding [5].

Table 1. Mechanical properties of carbon fibers compared with steel materials.

Material type		Density ρ (kg/m^3)	Tensile Strength σ_u (GPa)	Elastic Modulus E (GPa)	Breaking Length $\sigma_u/(\rho g)$ (km)
Carbon fiber	Standard	1760	3.53	230	205
	High strength	1820	7.06	294	396
	High modulus	1870	3.45	441	188
Steel	S355	7850	0.50	210	6
	Wire	7850	1.77	210	23

Table 1
Mechanical properties of carbon fibers compared with steel materials (Liu et al. 2015)

When combined with a thermoset or a thermoplastic matrix, carbon fibers make up a high-performance composite. In a fibrous composite, the fibers are the principal load-carrying constituents, therefore, the mechanical properties of a fibrous composite are, in general, dominated by the fiber characteristics (Ilankeeran et al. 2012). The mechanical properties of the composite may vary depending on the producers of the resin and the fibers and how the two are combined. As shown in Table 1, the tensile strength of carbon fibers can reach impressive values, as 7,06 GPa, being much higher than steel wires with 1,77 GPa, while their densities are much lower, 1820 Kg/m3 compared to 7850 Kg/m3. (Liu et al. 2015).

This project aims to exploit the tensile strength of carbon fiber composites to its maximum by applying it to a minimal design that reflects the material qualities.

Application in Architecture and Design

Carbon fiber composites have introduced new possibilities within the fields of architecture and design through their inherent capacity to form complex geometries with a programmed behavior. By controlling the directionality of the fibers the performance of a structure can be tailored to specific structural requirements (Prado et al. 2014).

In their research ICD and ITKE combine principles from biomimetics, material science, robotic fabrication, engineering, and architecture to create complex, lightweight fiber composite construction systems. They have explored both component-based fabrication systems as well as on-site continuous fabrication processes. The Elytra Pavilion, a lightweight glass, and carbon fiber canopy inspired by the protective shell of beetles (Prado et al. 2017) shows how larger fiber constructions can be realized with components. The ICD/ITKE Research Pavilion 2015, a carbon fiber pavilion inspired by the water spider, explores a different method as it was fabricated in-situ with a sensor-driven robotic arm (Doerstelmann et al. 2015).

The Fibre Facade Prototype, developed by the engineer James Solly (ITKE) together with FIBR GmbH, is a facade system demonstrator of carbon fiber reinforced polymer designed to carry the load of glass facade panels and expected wind loads for a building envelope. The visual appearance of the frames is minimal and emphasizes the high performance of the material [1].

Carbon fiber composite in a form of a yarn or a tow has been applied in a few furniture projects. Bertjan Pot's 'Carbon' chair [2] is an example of how traditional design can be revisited with modern materials. In contrast, Korean designer IL Hoon Roh's projects 'Luno' lounge chairs [3] and 'Rami Bench New York' [4] show how new design expressions follow new materials.

With carbon fiber comes a completely new aesthetics for lightweight structures. Although Pot and Roh explore the use of carbon fiber in their projects, they do not fully explore the minimal layouts made possible with the material as demonstrated in Solly's project.

Fabrication methods for filament materials

Carbon fibers can be, among other processes, winded, woven and braided (Teijin Carbon Europe GmbH. n.d.). Historically the processing of filament materials was executed by trained human hands, until it was automated during the industrial revolution, with for example the invention of the Jacquard loom.

The technological advancements of the past decades have opened up a new range of possibilities with regards to the fabrication for filament structures (Marshall Prado 2016). Automated tailored fiber placement allowed for placing the fiber in the ideal stress-load direction, and has resulted in successful, lightweight design projects, such as the three-legged stool developed at the Leibniz-Institut für Polymerforschung Dresden (Richter et al. 2015). Coreless Filament winding with 6-axis industrial robotic arms (Doerstelmann et al. 2015), aerial robots (Felbrich et al. 2017) and mobile robots (Yablonina et al. 2017) have proven successful winding methods for producing highly customized filament architecture without the use of molds.

In this project, the fibers have to be three-dimensionally woven, which requires a complex exchange of material, still not available as a robotic setup. This project serves as a small-scale proof-of-concept of a fabrication setup that should later be automated through a large-scale robotic setup. Until the computational tool and all fabrication parameters are adjusted, the fabrication is manually operated.

METHODS

Design method

Antoni Gaudí spent his professional career exploring the use of hanging models to obtain shapes in equilibrium. To conduct his experiments Gaudí needed a design tool that allowed him to carry out quick calculations and alter the design at will, obtaining equilibrated forms directly (Huerta 2006). The use of hanging models enabled him to shift from calculating two-dimensional arches with graphic statics to design and calculate spatial three-dimensional vaults. These space-hanging models applied the slicing method firstly used by Hooke in the last quarter of the 17th century, in which the vault is understood as the sum of a series of arches obtained by "slicing" the structure with a certain number of planes (Huerta 2006).

Gaudi's models were constructed hanging, achieving an equilibrated distribution of tensile forces, and when transformed into drawings for construction were flipped, producing a form ideal for compressive forces. As the goal of this project is to achieve the equilibrium shapes for tensile forces, the models remain in the initial hanging position, without being flipped afterward.

The proposed design method uses a similar approach to the above-mentioned "slicing" technique. In this case, parallel catenaries are formed by hanging strands with different lengths. While Gaudi shaped his catenaries by attaching sandbags to specific positions, this project uses non-elastic threads to pull each strand into the desired shape. At each carbon strand/thread intersection, a node is created at specific positions in space (Figure 1).

The nodes are then used to weave the catenaries together, forming a surface, which allows for the direct shaping of a 3d-grid in space.

After being cured, these first fibers are used as formwork, just like the weaving process of a cobweb, where the spider uses the first threads as the supporting structure for further weaving (Ali Askarinejad 2015). With this approach, it is possible to create a complex three-dimensionally weaved surface independent of its frame. In most winding systems, every node is related to a mechanical anchor point (usually a metallic spacer or a bolt). However, in this case with a small number of anchor points in the frame and on the floor, a large number of independent nodes are created

From this design logic, many resulting grid-configurations can be formed. To enhance the design process and inform the decision making, a computational tool was developed.

Integrated design and form-finding tool

Initially, a simple computational tool was developed to enable a fast generation of designs. It was scripted in Grasshopper with a custom Python component. The input parameters were the number of fiber intersection points in y and x-direction connected by lines. The z-height of each point could be interactively changed to form the desired chair.

Although this method proved to be useful to some extent, the strategy evolved from the manual adjustment of points to a form finding method that to a larger degree reflected the design and fabrication methods.

Figure 1
Design principle, each carbon fiber strand is shaped by being pulled in a specific direction

Using the Finite Element Analysis (FEA) plugin Karamba, gravity-based forms following the hanging chain principle were generated. The catenaries were acquired from the form found mesh under gravity (Figure 2). The design of the chair could interactively change by adjusting the mesh resolution and the position of the mesh anchor points. While the Z and Y-Axis affected the lateral section (Figure 3a), the X-Axis affected the width of both the seat and backrest (Figure 3b).

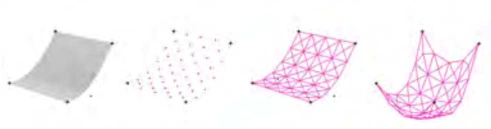


Figure 2
Form finding tool overview: mesh is created with 6 control points. The squared grid is subdivided forming a triangulated mesh. Gravity load is applied to the mesh.

The mechanical properties of a non-cured carbon fiber composite were considered as input. In this case, Young's Modulus (25000 kN/cm2) derived from the pure fiber without considering the properties of the resin.

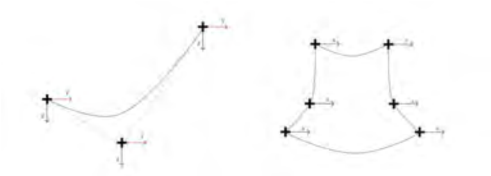


Figure 3
The Z and Y-axis affect the lateral section, and the X-axis affects the width of the seat and backrest

Although computational methods for hanging chain models are well established in the computer graphics community and the animation industry (Kilian 2004), they were rarely targeted for architectural purposes. Axel Kilian applies this method as an interactive tool for designers, enabling a playful exploration of evolving structures (Kilian 2004).

Figure 4
Fabrication setup

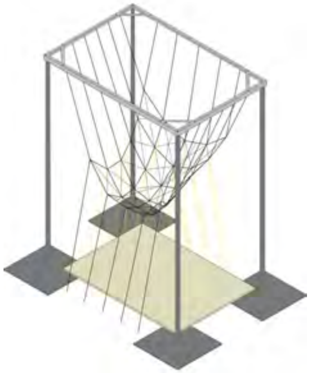
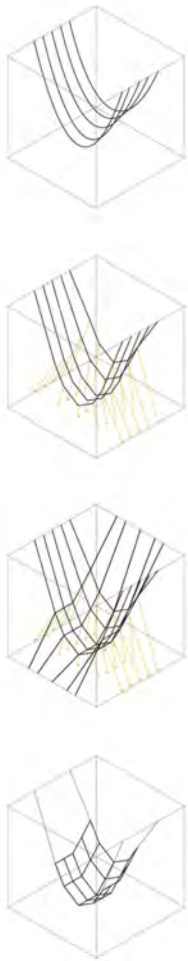


Figure 5
Fabrication
procedure



Different from Killian's approach, where he applies different loads to specific elements achieving more complex geometries, the design and fabrication setups proposed here imply in a simple combination of parallel and perpendicular catenaries, what can be obtained digitally considering only the self-weight, without the addition of any extra load. This strategy offered an accessible and fast way to visualize possible outcomes.

Fabrication method
Parallel strands of carbon fiber pre-impregnated with epoxy resin were hung on nodes attached to the top of a rectangular frame. The length of each strand was predefined. Subsequently, each of them was shaped with multiple non-elastic threads attached to the ground (Figure 4). By differentiating the length and spacing of each tensioning thread the form of the carbon strands were determined (Figure 5). At each fiber-thread intersection, a new node was created, and these were then used to weave the network of fibers between the initial strands composing the seat and backrest.

After curing, all threads and carbon fiber strands that were attached to the ground and the frame were cut away. Finally, thin metal wires were connected to each of the four corners of the chair and the ceiling, and allowed it to hang and swing.

Figure 6
Prototypes 1 & 2, 1:10

Figure 7
Prototype 1:5

Figure 8
Exploded isometry of the four winding steps: initial strands, perpendicular strands, diagonals, reinforcement.

RESULTS

Case study: The hanging chair

Physical prototypes and material tests

Both the design method and the fabrication process were explored and tested with physical prototypes of different scales and materials. With the making of the prototypes, it was possible to understand the results of different syntax strategies as well as fiber interactions that resulted from it.

Two 1:10 physical models (Figure 6) were developed using a wooden frame, foam board and non-elastic cotton thread impregnated with resin. The purpose of these models was foremost to explore the design outcome, not considering the material properties.

Subsequently a 1:5 model (Figure 7) utilizing the actual material was produced. Important takeaways from this process were that the sliding of the ropes would cause fibers breakage, that the fabrication process must be undertaken with multiple curing sessions, and that it must be confirmed that the spool can pass in between all fiber intersections. Additionally, a better understanding of the winding syntax was acquired.

Full-scale prototype

In preparation for the full-scale physical prototype, a digital design was generated. It was primarily based on the small scale prototypes and created with the initial version of the form-finding tool. A 4x5 triangular mesh was defined and gravity load was applied, generating its final shape. The obtained design functioned as a guide for the winding sequence and provided the necessary practical information such as the length of the initial carbon strands.

When the digital design was ready and other off-site practical preparations for the fabrication were concluded, a workspace consisting of a frame and a screw hook board was constructed. The frame was composed of four poles connected at the top with a lightweight, rectangular metal frame. In between the poles, a piece of plywood with distributed metal screw hooks was placed. The screw hook board allowed the tensioning threads to be attached to the floor.

To guarantee a clean fabrication process and minimize resin dripping, the carbon fiber yarns (Tenax® E STS40 F13 48K 3200tex) were pre-impregnated with epoxy resin (3 parts of EPIKOTE Resin MGS LR 135 + 1 part of EPIKURE Curing Agent MGS LH 137, both produced by Hexion Inc. Pot Life: 8 hrs.) wound on spools and frozen (Figure 9). The freezing period varied from short (30min) to long (12hrs), both presenting good results. However, it should be noted that the freezing time of pre-impregnated carbon fiber varies according to the resin type and producer. The freezing stops the hardening process and allows a clean preparation of the composite prior to usage.

When the pre-impregnated carbon fiber spools were ready, the first six strands were wound, shaped and then left to cure for 24 hours in room temperature. Afterward, the perpendicular strands and the diagonals forming the triangulated pattern of the seat were woven over-and-under the cured fibers and left to cure for 24 hours (Figure 11).

Following the second curing, all of the connecting fibers and ropes were cut away. The metallic loops (Figure 10) were installed during the winding process in the four corners of the chair allowing the connection of wires that enabled the chair to hang from the ceiling and swing when installed.

In total, the chair was suspended in air anchored to 17 points from the upper part of the frame and put in tension with 30 screw hooks on the ground. It measured 90 cm by 90cm, had an impressive total weight of 300g and could hold the weight of a human body (60kg) (Figure 14).

Computational tool 2.0

After the completion of the physical prototype, it became evident that the design method/process would benefit from a more sophisticated computational application. The initial tool provided an effective way of generating geometries, but not a way of structurally evaluating and optimizing them.

Figure 9
The prepregg spool, ca 50m of carbon fiber

Figure 10
The metallic loops were installed during the fabrication process

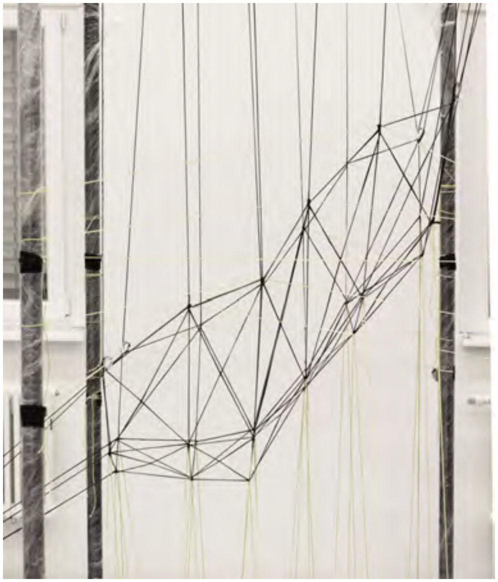


Figure 11
The final curing of the chair in room temperature

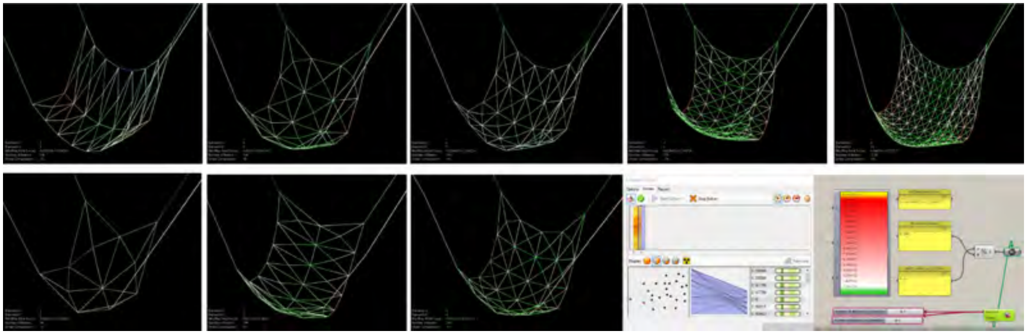


Figure 12
Structural optimization tool overview: evolutionary solver checks for the mesh configuration with the less percentage of elements under compression

The initial tool was then expanded and resulted in an interactive 3D-modeling interface that combined design intentions with structural optimization.

The structural optimization takes place by disassembling the form-found model in new elements and simulating the deformation of the chair under a load of a human.

From this moment on, the material properties of the model change to the mechanical properties of a cured carbon fiber composite, with Young's Modulus = 8700kN/cm2. To enable the chair to realistically deform, the anchor points are transferred to points representing the connection to the ceiling and attached to the previous anchor points with four new elements.

The simulation returns which elements are under tension and compression when deformed. Figure 13 shows an example of a chair model before and after deformation. The results obtained from the FEA analysis were then connected to an evolutionary plugin (Galapagos). Taking into consideration the goal to have the model working under tension, the fitness criteria was set to minimize the percentage of elements under compression. The parameters, or genes, allowed to change the subdivision of the grid, changing the mesh configuration (Figure 12).

The use of a generative algorithm offered a quick validation of different design iterations while guaranteeing structural performance.

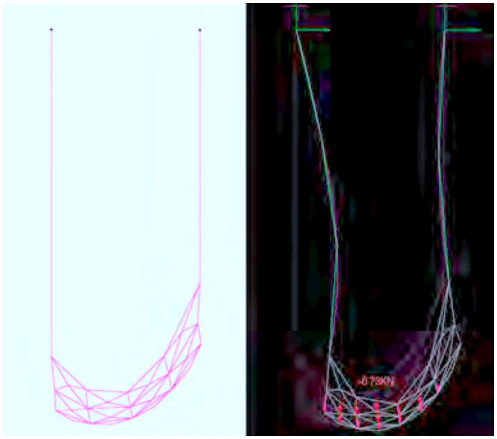


Figure 13
Comparison of the model before and after structural simulation

DISCUSSION AND CONCLUSION

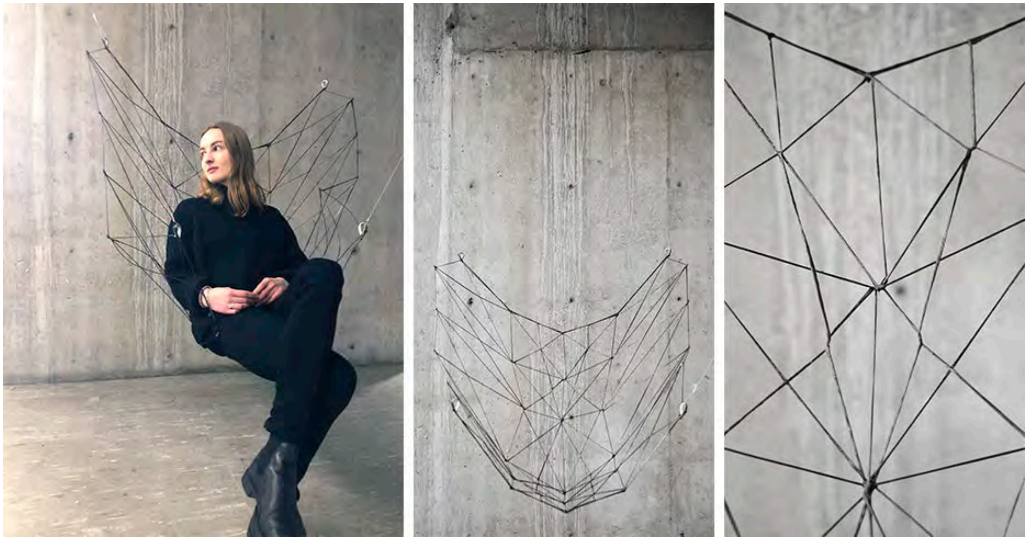
The built chair was incredibly light (300 grams) and able to carry the weight of a person.

Nonetheless, the syntax and topology optimization still need further development and some failure points were noticed.

With the proposed fabrication setup it was not possible to accurately convert the digital design to the physical chair. It proved a challenge to symmetrically pull the tensioning threads without causing individual fibers to break.

Although the digital model provided the target length of all fiber strands and tensioning threads,

Figure 14
The final prototype



it did not return the angle between them and the hooks. Consequently, the placement of some threads had to be improvised during fabrication, which lead to imprecision. This data could be implemented in the further development of the tool.

Several of these challenges could have been tackled with a complex robotic fabrication setup consisting of two robots collaborating. However, as mentioned, the setup does not exist and it was not the goal of this project to develop one. Nonetheless, it could be an interesting continuation of the project to develop such a setup.

Aiming for a more informed structural optimization method, the future development of the tool could consider the use of a multi-objective evolutionary plugin. It would allow the analysis of the elements under compression together with the values of maximum displacement and produce a more precise result.

Another relevant next step would be to research the use of more environmentally friendly filament materials such as natural fibers or carbon fibers retrieved from lignin. Because the source of these materials are renewable, they could represent a more sustainable solution for lightweight filament structures (Dahy, 2019).

Gaudí innovates by using the concept of catenary arches to integrate the structural design in the process of design. This project aims to make the realization of equilibrated forms accessible, and to combine design intentions and structural optimization through physical and digital models.

The technological advancements of the past decades have allowed us to integrate the different aspects of a design process. By alternating between digital and physical design spaces, the design process can be significantly more informed. The goal of this paper is to present a solution in which the material is not a mere bystander, but plays the main role by informing every aspect of the design and fabrication process, and with this hopes to contribute to the discussion on integrative computational design.

AUTHORSHIP INFORMATION

Duque Estrada and Wyller contributed equally to this paper. Concept, design, methods and prototyping of the project, as well as writing the paper was done by the two together. Hanaa Dahy edited the paper and supervised the educational course in which this prototype was produced.

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Challenges - ART AND DIGITAL POESIES

Singing Cans

Prototyping an experimental wind instrument through parametric design integrated with field experiments

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We present a study of how parametric design can be linked to field experiments where ready-made plug-ins are not available for performative modelling. The study centres on prototyping `Singing Cans' - an experimental wind instrument made with an assembly of drinking cans that can produce sounds in recognizable pitches by interacting with airflows. We describe how field experiments conducted in a fluid flow lab can generate performative resources linkable to parametric design modelling. In Singing Cans, we focus on how to get airflow through a hole made on drinking can to make sounds. The prototyping process involved a lab-based calibration process to establish the relationship between the air volume of a can, measured by water-filling, and the pitch produced, measured by the Tuner Lite by Piascore. The field experiments resulted in a dataset capturing a can's sound-making behaviour in terms of water volumes and pitches. A parametric model that can take in wind data generated by a CFD package and output a 3D frame for site-specific cans installation is presented.

Keywords: *parametric design, field experiments, experimental wind instrument, fluid flow instrumentation, sound production*

RESEARCH CONTEXT: SITE-SPECIFIC URBAN WIND ENVIRONMENTS

We propose an idea of urban musical instrument that originates from urban wind environments.
The urban wind flows are seen as a sound-making system that drives an array of disused drinking cans. We consider the idea in an urban context where the wind flows exhibit various patterns shaped by different building densities. As shown in Figure 1, the higher aspect ratio (H/W) can create a stable circulatory vortex between buildings (Oke 1988).
Therefore, we are interested in looking for narrow streets as potential installation sites. The design challenge here is how to develop a generative system for configuring recognisable pitches generated by wind

flows for people to hear and interact - Singing Cans.

In general, the principle of sound production is related to the vibration and movement of the air molecules in the surrounding area. For instance, in flute playing, the lips direct the air stream against the thin edge of the mouthpiece, raising the resonance of the pipe to produce a tone (Farnol 1941). A general name of the instruments that produce sounds through fluid dynamics is called reustophones (Mann and Janzen 2015).

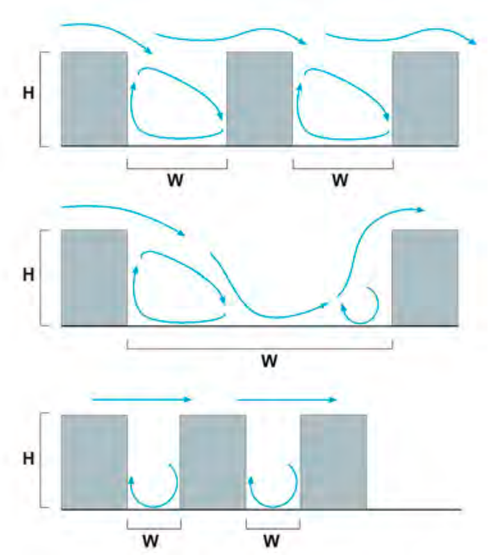


Figure 1
The wind flows characterised in the building-street aspect (H/W) ratios (after Oke 1988)

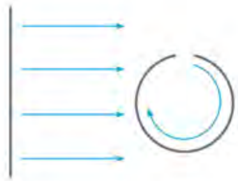


Figure 2
Wind flows through a can with a sharp edge cut open

In our project, the design of a frame is required to assemble Singing Cans in a site-specific way and maintains the same wind pattern after installation. By following the flow regimes, parametric frames are created and placed in a specific location with the extract wind data from the CFD simulation.

In Singing Cans, we focus on how to get airflow through a hole made on the cans to produce sounds. Aluminum cans were selected as the main form and material because it was easy to find them from recycling points. To assemble the cans into a site-specific installation, we focus on how to get the wind data from the site and then use them to generate a frame. This paper shows (1) how we catch the airflow to produce sounds following the principle of the music production of the flute; (2) how we create the installation frame based on CFD simulation of urban microclimate, following the adaptive parameters in terms of the size of the frame and cans.

SOUND-MAKING CANS

From a basic study of sound-making with cans, we moved to generate pitches from cans. This involved a lab-based calibration process to establish the relationship between the air volume of a can, measured by water-filling, and the pitch produced, measured by the Tuner Lite app by Piascore. The field experiments resulted in a dataset capturing a can's sound-making behaviour in terms of water volumes and pitches. When the wind blows through a pipe, it does not produce sounds all the time; only when the air is resonating in the chamber, then noises could be heard (Benade and French 1965). The phenomenon can be further explained by Reynolds number in fluid dynamics.

It was found that the relationship of the fluid density of air, the flow velocity and the diameter of a pipe influences turbulence flows in the pipe (Upp and LaNasa 2002). A pipe sounds when the Reynolds number reaches a certain level, and sounds could be heard as the air inside the pipe is vibrant and resonate. In Singing Cans, we found that the angle of airflow into a can is an important factor. The airflow going through the sharp edge cut open on a can becomes turbulent from a laminar state (Raman and Srinivasan 2009). In order to identify certain valid angles of the input airflow, we created a hole in each can and we tested them by rotating the cans in different directions.

Figure 3
Wind testing of cans in the Lab

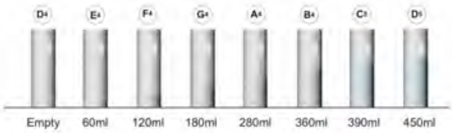


Figure 4
Pitches in Cans

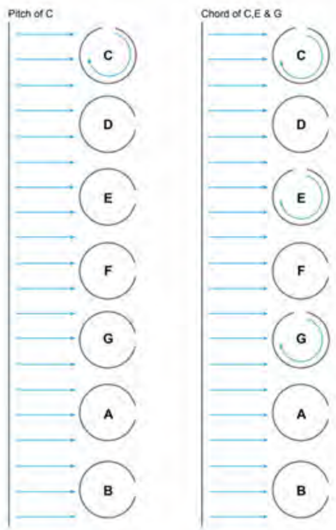


Figure 5
Sound production with the cans

Our lab experiments show that the cans produced sounds within a particular range of 60 to 90 degree. Throughout the testing, we concluded that the can should be tangent to the airflow as indicated in Figure 2.

In the lab, a wind tunnel (Figure 3) was used to measure the pitches produced by the cans. In the beginning, a single can of 330ml was tested. We first noticed that a certain angle of the hole in relation to the airflow, around 90 degrees (Figure 2), was required for the can to sound optimal. As the wind tunnel can be controlled to produce different flow speeds, we investigated the measurement of pitches in 445 Hertz frequency level. When the wind speed was high enough, the result was a louder sound with no stability and sometimes the pitch was converting into noise. Therefore, the wind speed was stabilised at approximately 7.5m/s for taking the measurements as the sound data.

Our laboratory experiments provided useful numerical data and knowledge on the conditions of how a can produces different pitches. Cans with different sizes were further tested. The observation was that different sizes produced different pitch readings. As expected, cans of fewer air volumes resulted in higher pitches. In order to obtain a more accurate pitch measurement, water was used to control the air volume inside the can. To produce a wider range of notes, a can of the 568ml volume was tested. Eight cans of the same volume size, filled with different volumes of water inside, were tested separately to produce one note. A range of eight musical notes (D4, E4, F4, G4, A4, B4, C5 and D5) was then generated into a dataset (Figure 4). Subsequently, we control the rotation of the cans to produce seven pitches or the chord of pitches like Figure 5. Each can was programmed to be *on* or *off* for a certain duration to create the melody.

SENSING CURRENT WIND DATA

For further development, the ranges of airflow velocity and direction were considered as the essential input data to a generative sound-making system.

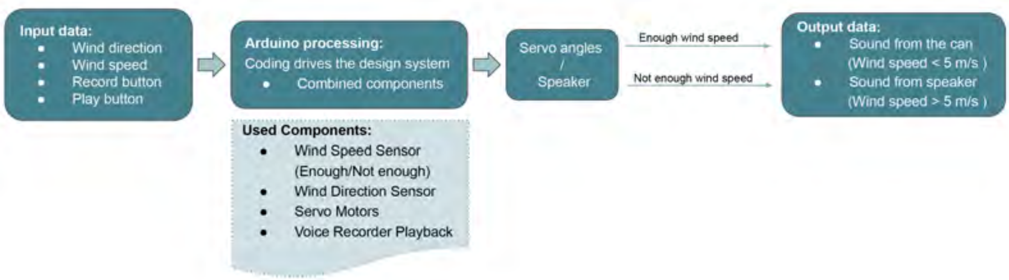


Figure 6
An Arduino-based wind sensing platform

Table 1: Arduino components

	Input	Output
Arduino Sensors / components	1 Anemometer (Wind Speed)	1 Relay
	1 Wind Vane (Wind Direction)	3 Servo motors
	2 push buttons	1 ISD1820 Voice Recorder Playback
	Additional components: 1 Mega 2560 board, 1 big breadboard, 1 small breadboard, 1 power supply, Resistors and Jumper wires.	

Table 1
Arduino components

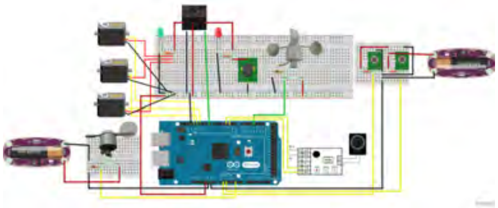


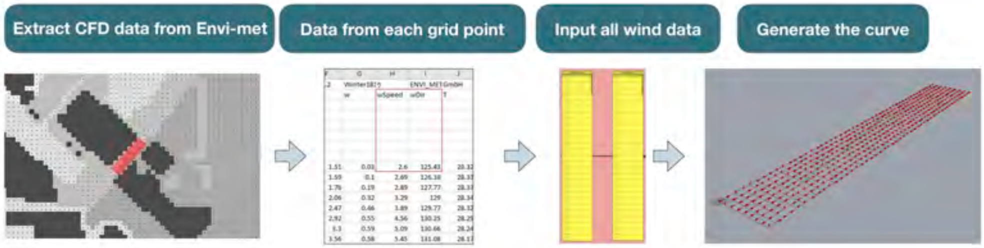
Figure 7
Arduino assembly diagram

Figure 8
Sensing wind direction to rotate the cans

Arduino is a useful resource for us to construct a wind sensing platform. The application method comes from an anemometer and a wind vane. The process shown in Figure 6 starts with the current wind speed and wind direction as the input data to the Arduino system. The microcontroller activates servo motors to rotate the cans following the angle reading from wind vane direction. We also develop an alternative method: If the wind velocity is not high enough for the cans to produce audible sounds, a speaker will be activated to play pre-recorded sounds instead.

In prototyping the interactive Singing Cans installation, we have utilised a number of physical computing components (Table 1). These components are divided into input and output groups. Figure 7 shows how the system works. The process begins with the input data of the wind direction and the wind speed. Two push buttons were used for sound recording. When processing these data, the system makes two decisions based on the inputs (Figure 8): (1) if a wind

Figure 9
Extract wind data from Envi-met



speed of 5 m/s is reached, the cans will be rotated to align with the wind direction. As such, the cans will be able to generate sound from the airflow; (2) if a wind speed below 5 m/s is measured, then the speaker is activated to play the recorded sound file.

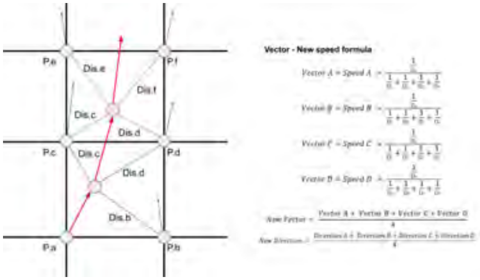


Figure 10
The formula for calculating the new vector

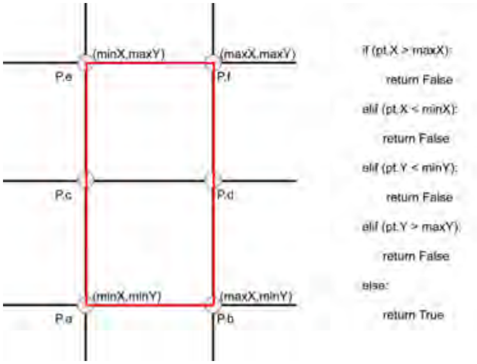


Figure 11
The way to define the boundary

PARAMETRIC MODELLING OF THE FRAME DESIGN

In order to determine the geometry of a frame design for site-specific installation, we first used ENVI_MET (a CFD urban climate modelling package) to generate wind data. The simulated wind data were then imported to a parametric modelling process using Rhino-Grasshopper (Figure 9). The data comes from ENVI_MET software which investigates CFD simulation in climatological conditions [1]. Then, a uniform rectangular grid with the spacing of 1 meter along the x- and y-axis was used for both modelling and simulating in ENVI-met. Each grid point was the observation point of wind data for the speed and direction. Finally, the simulation results were extracted into spreadsheets for following wind-informed parametric modelling design in Rhinoceros 3D and Grasshopper [2].

With the initial grid-based wind conditions, data interpolation was implemented with the inverse distance relationship to the existing grid points. In the 3D modelling environment, wind data is represented by the vector. The wind speed defines the length of the vector and the wind direction defines the angle of the vector. There are two customised procedures implemented in Python within the Rhino-Grasshopper scripting environment [3]. The first is to generate a parametric curve following the wind direction and speed. We recursively define new vectors with the closest four neighbours while moving forward. The second step is to determine the termination criteria given the desired boundary conditions.

Figure 12
Two locations on the University of Sheffield campus selected for Singing Cans installation

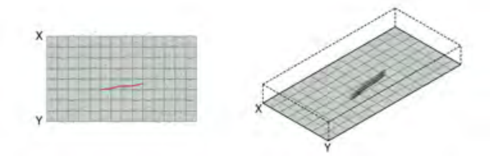


Figure 13
A horizontal frame

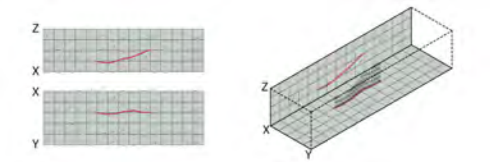


Figure 14
A vertical frame

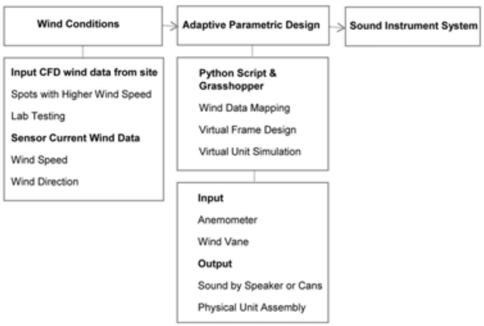


Figure 15
The overall workflow of the Singing Cans prototyping

The inverse distance formula is used to calculate the distance relationships from a target location with four closest neighbour grid-points. These relationships are later employed to define new interpolated wind direction to move the target point forward with a unit length, as shown in Figure 10. This step is executed recursively until the termination criteria are met. By specifying the desired boundary as showed in Figure 11, the termination procedure checks whether the new target location exceeds the set boundary. If true, the curve generation will be terminated.

THE SITE ADAPTATION PROCESS

Based on specific wind data, discovering the ideal architectural shape can be realized by parametric modelling (Kormaníková et al. 2018). We adopted a computational fluid dynamics (CFD) site modelling approach to the frame design. For meeting the design and environmental requirements, the chosen site needs to contain two conditions: (1) to select the city corner as the application scene; (2) to obtain a relatively stable high wind velocity environment, the site needs to present a narrow and long corridor space. Considering the above considerations, two locations on the University of Sheffield campus were selected to collect wind data and generate structural forms (Figure 12).

Due to the need for adapting to different site characteristics, here two different vertical and horizontal structures were proposed. Site 1 provides a wall at a height of approximately 1100 mm, and the installation can be placed directly above this wall, so a horizontal frame is designed (Figure 13). At site 2, the installation is directly placed on the ground, and the frame structure needs to have a specific height. The vertical height of the frame is generated by the XZ section of wind data to determine the height of each column, so a vertical framework is shown in Figure 14.

ON-SITE DISPLAY OF URBAN MUSICAL INSTRUMENT

The development of 'Singing Cans' installation combines virtual and physical prototyping to test how digital tools can successfully activate the interactive features (Figure 15). In this project, we start by identifying locations with higher wind speeds on campus to investigate on-site wind conditions through simulation. We then incorporate the simulated data to formulate the wind flows into parametric shapes for the structure frame design. The proposed frame de-

Figure 16
A horizontal frame rendering on site

Figure 17
A vertical frame rendering on site

sign is envisaged to receive enough wind speed and not to interfere with the existing wind conditions on site.

CONCLUSION AND FURTHER DEVELOPMENT

The Singing Cans urban wind instrument can be further improved, by implemented alternative rotation methods to generate different sounds of various volumes in the cans and use more push buttons to switch the rotating patterns of them. For further research, an Internet of Thing (IoT) user interface could be developed to extend the interaction design. The IoT layer will link up multiple installations at different sites (Figure 16 and Figure 17). The mobile device based application can display real-time wind data for the users as hints to navigate through the city's wind environments. Thus, the Singing Cans urban musical instrument not only provides a system for the public to interact with the wind and sound environments but also offers a practical facility to collect wind data.

ACKNOWLEDGEMENTS

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The Digital Street Lab in a Box

A tool-kit for surviving in the contemporary public space

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This paper describes two workshops raising awareness of the complexity of the interactions between digital and non-digital space, networks, devices, and systems. The exercises are included in broader research that deals with the human condition in the contemporary and future cities, focusing on the relationship between public space and weaponized data as a threat but also as an opportunity to act. A new way to understand and operate the street must be developed, with new epistemic assemblages, which allow us to avoid dystopian or technocratic visions in order to think collectively in our future human habitat. We offer here a toolkit, a series of strategies, to cope with the overwhelming complexity and act. The research is still open and the present paper shows the most recent experiences of a twenty-year journey.

0. The city is quickening. We hover between built space and media places. Placemaking that takes no heed of the knowledge environment is no longer pertinent or relevant. In the era of the fourth industrial revolution and pervasive computing, we need better strategies to deal with the built environment, establish a meaningful presence in it and eventually to produce it. The technological forces currently in play are uncontrollable: uncontrollable by those who have designed them, and uncontrollable by those who own them -this is the new means of production-. What this means to us is that we no longer have the capacity of a synoptic vision. The omniscient presence and mediation of software in every aspect of human life and interaction. Its effect on what is often claimed as the space of interaction par excellence is what we have called “the Algorithm that ate the Street” (Guzzardo, 2008, 2012, 2018). A diagnosis of the urban habitat. Beyond the fact that we are understanding what is underway, the certainty that we are being changed as a result of these technological forces makes imperative the need to act.

Acting within a certain conceptual framework, a provisional diagnosis while recovering the reactions and indications of such intervention in the real world seems the only possible attitude in front of a fast-changing scene. Issues are conceptually identified but not intensely explored through design, design tools and thematic categories for any device on the street are also fragmentary and provisional. As a result, any pretension of a problem-solving strategy is futile. This is where the proposed attitude follows some metaphorical enunciations that characterize the action. Triage is our reference to a situation where diagnosis and therapy overlap. Recursion is a reference to provoked situations where a jump from the material reality of the world to the virtual places and mappings takes place as a therapy to the digital bubble inhabiting. Such metaphorical references or conceptual extensions from different epistemic fields have been used as a way to set in motion the design processes that are the focus of our didactic experiences and are vectors that push the research, action, and production we call the DSLB.

1. The Digital Street Lab in a Box (DSLB) (Guzzardo, 2004b, 2018) proposes a new place-making action plan for a withering public sphere. It goes after the need to develop new epistemic assemblages - street probes and sensors- for navigating a landscape of space and information. It's best described as a tool-kit. Kit to be used in order to survive in the contemporary public space. The tools include hammers and triage devices, both are needed to deal with "weaponized data" (Cook, 2018) -those predictive machines whose goal is to create a perfect model of who you are, what you want, and what you are going to do-.

The central idea is an urban-stage for performance with roots in the non-physical public space which allows embodiment of that virtual realm and takes some eventful condition in the street. Finally, this is a strategy for awareness based on recursion, rooted in a provoked distortion, a disturbance in the system. This is intended to open thresholds between both layers/worlds/systems which are brought by the action of the metaphoric character of the "trickster" (Guzzardo, 2004a, 2012). The trickster a sort of culture system hacker, creates a disturbance that exposes by displacement the relations between both spheres.

The preparation of Storyboards that lead to this urban-stage is Among the list of the previous experiences. This could take different meanings according to what specific field of action undertakes their development. They could be programmatic enunciations for designers, situations for the development of performance stories for a theatrical performance group, an outline of spheres and digital/real world situations/data to be linked by programmers and developers, etc.

The DSLB storyboards can be best described as a type of Media and Information Literacy Street Algorithm: a series of steps to visualize the impact that digital networks / the data cloud have on the city and ourselves. "Media and Information Literacy recognizes the primary role of information and media in our everyday lives. It lies at the core of freedom of expression and information - since it empowers citizens to understand the functions of media and other information providers, to critically evaluate their content, and to make informed decisions as users and producer of information and media content." (Grizzle et al., 2013). The DSLB storyboards were used in the workshops to introduce architectural student and professors to think in terms of MIL competencies. They provoked a recognition of: a) how the gale force of accelerated code is altering conduct and consciousness, b) how new infrastructures and interfaces on the street can cultivate MIL storytellers and audiences.

The development of the DSLB includes installations, workshops, and presentations all around the world since 2002 (Guzzardo, 2002, 2003, 2004, 2006, 2008, 2012, 2015, 2018). Each part of the path has gone through different aspects of the problem, from purely legal issues to multimedia artistic expressions, including work with designers and programmers. This paper focuses on the two most recent workshops made with a group of eighty students at the School of Architecture of the National University of La Matanza (UNLaM) and a group of more than a hundred students at the Architectural School of the University of Buenos Aires (UBA), and its outcomes. That includes the study of the literature around urban performance, street art, digital installations and multimedia artifacts (Agkathidis, 2014; Artopoulos, 2007; Augustynowicz, 2010; Briones, 2007; Canavezzi, 2013; Del Signore, 2009; etc.).

It is important to clarify that the specificity and scope of these exercises do not allow us to work on the totality of the program developed above. Each workshop functions as one more piece that is added to a larger whole, and that finally aims to reflect, raise awareness and call to action in relation to problems that we consider to be critical. Acknowledging the difference between moments of definition and precision as opposed to moments of opening and exploration (metaphors, images, analogies), but rescuing their pedagogical and research function (tropology). Therefore, we defend the need for a certain degree of indeterminacy and openness to interpretation in the process of theoretical construction of the research work in progress.

2. The first workshop (UNLaM) was an open-ended experience. While a sequence of propositions was made to participant/surveyors/designers, many instances were redirected as the didactics unfolded. The original set of guidelines was roughly defined by the conceptual framework of our DSLB project and a set of activities that we understood would introduce an awareness of the issues in such a way that they could lead to an investigative and creative interest. The projected sequence was:

- Open a set of reflection/action activities that focused on the configuring power that technical-material networks (infrastructure) have on the configuration of public space.
- Establish a parallel for reflection/action between the effect and role that these physically present- although mostly invisible- infrastructures have had in our embodiment in public space , and the new and increasing presence and influence of Big Data, Social Networks, Surveillance Systems, etc. which by force of accelerated code are altering conduct and consciousness in a digital public space. A presence that is veiled for the simple observation of physical space, but that through the previous activity would be more easily accessible to them.
- Set in motion design actions that challenge their invisibility by putting forward their performative power as devices in the street. The initial goals were to make the networks of the urban fragment visible, to detect the devices and link the flow with their performativity.
- Exploring design possibilities for making visible at a performative, real-world level the presence of this public space, creating the opportunity to jump in a recursive cycle from one layer to the other.

The work began with the construction of cartographies of urban fragments based on inquiries, detection of signs, surveys, etc. They worked with different layers, based on a fixed use scheme. The survey was conducted by each group on urban fragments of approximately nine blocks based on the symbolic, political, social and cultural relevance of the territories. The kind of infrastructure or physical signs were often linked to what made the fragment relevant. Edition and enhancement of those signs that were surveyed were the strategies for making the networks and devices visible.

At this point, a connection through analogies and reflection on personal experiences with the presence of the “digital cloud” was introduced, and a more specific reference to the performative program included in the DSLB project was made through examples and review of what has been so far produced. In many cases, a connection was established between the site relevance and the first ideas for these performative proposals. This evolved in a design proposal with the intention of implementing an urban action. The cartography (the visibilized-unveiled) was the input to achieve a place-event oscillating between the performatic and the urban intervention.

The proposals insisted on experimental processes that develop determinations to make a semiotic leap (Martin Iglesias, 2013). This leap is the transposition, from the existence of the unveiled network, towards the denaturalization of the fragment in order to operate it as an event. The design process built that transposition of senses to create action/installation -interphase and interface- in an immanent here and now. Therefore, the design focused on two aspects: the stage and the storyboard.

The stage, as a support for the technical-material elements of the project, is based on a kind of technological neo-baroque setting. The street, the public space, is the stage. However, so is the device mounted on that given stage. In this case, the site was considered with its physical and non-physical pre-existences, which were operated or modified by design. Each project defined, based on its proposition, a scale of operation. From large infrastructural scale to a minimum interpersonal one.

Duration of the performative operation had different outcomes, from permanent presences in space to the mobile and ephemeral. The project proposal, the medium-device-event is designed (with its material characteristics) so that the site is performed as an edition of its pre-existing characteristics, qualities and meanings attached. The street as a stage goes back to the history of the city and a long line of theories about the construction of the city. However, it is particularly useful because it offers a simple metaphor for what happens on social networks or the digital "public space." Furthermore, the need for this representation should be immediately understandable to architects and designers who think not only about the fixed but also about what happens/-takes place.

Figure 1
Image by Rodriguez_Pockay_-Rivero_Roldán (UNLaM)

The narrative of the performance was developed in a storyboard format. Conceived as vaudeville or as theatre play it becomes an embodiment in the street that implies a jump from one layer to another in a recursive sequence. Real things and real bodies following create a displacement that breaks media bubbles. The link to the idea of the trick and the trickster operates here as an explanation of how the use of the designed devices and performative actions should work as an enticement, an event of discovery, an opening into an otherwise veiled dimension of the invisible networks in public space.

With a multimedia framework, the storyboard-script consisted of the description or narration of the actions that would be generated by the media-device-event. As a guide or criteria computer, we posed the following questions: What situations will the media-device-event generate? What actions? How will the user act with the artifact? What will the performative aspects of the physical action (actors creating actions and relationships) be? In short, in this script, the actions generated by intervention-performance and the consequences of those actions are designed. These consequences would be inferences or a series of inferences, assumptions of what is going to happen -the effects of interactivity- which must be written and represented in the storyboard-script.

The stage and the storyboard-script could then be explained differently with reference to the idea of the trick and the trickster. The physical support of the trick and the effect of the trick (inferences). How does the trick work? How does it perform? What effect does it generate? These questions point to the connection between the two levels handled by the trickster: visibility and invisibilization, as well as the connections or collaborations that the different types of networks have with each other. Finally, the students delivered intervention-performance projects in different formats and multimedia formats. In some cases, it was possible to advance in the staging of the project, so they also delivered the records of implementation and action, as well as the intervention and effects on the site.

The direct results were a series of storyboards (graphic anticipations of things foreseen, scripts that address time sequences and/or algorithms that generate events) in their different manifestations: drawings, videos, animations, stage designs, etc. These storyboards were then prepared collectively, rewrapped with new editions, overlays, collages, and glitched-recordings. The results varied in quality and originality, but most of them fulfilled the main goals of the workshop. We were able to observe that the understanding of the complexity of contemporary public space increased significantly, as did the awareness of the need to act on it beyond the mere critical resistance.

Figure 2
Image by Acosta_Vega_-Carenzo_Petkovsek (UNLaM)

This awareness implied not only the recognition of the impact of technologies on the discipline and the human habitat but fundamentally the design of performative alternatives on technological devices. The strategies deployed focused on multimedia experimentation and tropological research (Martin Iglesias and Voto, 2019; Hillis Miller, 1991). The design work and modes of presentation tended towards hybridization of media and formats (Martin Iglesias, 2015). The wide range of possibilities spanned from the analogical edge of the physical model to computational simulation, including different collage, montage, image, and video editing techniques. This multimedia approach was instrumental in sustaining the simulation of the future urban installation/intervention.

The workshop focused on the strategies (not the issue, subject, content, object or results). Strategies to get out of common sense, or step out the naturalization of the contemporary human environment. The strategies are related to a playful attitude, which can be represented by the trickster, the hacker, the homo ludens (Huizinga, 1955), the grave-merry man (Rahner, 1972), dodging the automated criticism. The workshop can be seen as an experiment in the sense that it does not attempt to confirm pre-established hypotheses, but instead seeks to generate perturbations in the system to measure and characterize its effects.

The strategies based on the disturbance of the system are the most appropriate for complex systems such as those that contain the human habitat. In a real holistic approach, we cannot fully understand complexity; you have to act and then draw conclusions, to recognize the dynamics, to react and to introduce changes in the system. We start from the human inability to fully know and understand the complexity and operate it. In this case, we worked with socio-technological systems, but it may apply to any system.

3. The second workshop (UBA) was called "urban retro-utopias in the global south" and was based on the results obtained in the previous workshop (UNLaM). Each project was assigned to a group of students with a description of their characteristics and objectives. These projects served as a starting point to reflect on the relationship between technical devices and urban space from a series of theoretical classes. The general framework of action proposed referred to the notion of retro-utopias to think of a relatively distant future that establishes paradoxical relations with the past (futurism burdened with anachronism), which characterizes most of the non-hegemonic expressions of our global south.

Then the guidelines of the practical activity were launched, which consisted in designing in greater detail and specificity the technical devices that appeared suggested in the projects of the previous workshop, with the purpose of advancing in the process that brings us closer to the actual materialization of the artifacts. This approach did not pretend to be pragmatic but proposed another drift through the notion of technical fiction. This notion served us so that the approach to the device was technical (looking for precision and detail) at the same time that it contained a high degree of fictionality (which allowed us to design speculatively outside the logic of problem-solving).

Figure 3
Image by Gonzalez_More_-Lodigiani_Guillermet_Guzman_-Guzzo_Gonzalez_-Mantei_Suarez (UBA)

The final objective of the exercise was to produce the technical documentation (blueprints) of the corresponding to assigned projects. This technical documentation had to use the graphic language of the technical documentation (with all its clichés and stereotypes) to achieve the plausibility of the proposal. This verisimilitude aims to reinforce the feeling of the feasibility of these devices that are clearly fictional. For practical implementation, students were provided with access to folders in the cloud where they could find theoretical, architectural and technical-fictional references. These included texts by the authors, projects by Archigram, Superstudio, Alejandro Burdisio, Giovanni Battista Piranesi, Étienne-Louis Boullée, Leonardo Da Vinci, and other utopian architects, as well as examples of representations and illustrations associated with technical fiction.

The students began studying the assigned projects, and once they understood their purposes and the importance of the technical devices involved, they began to design these devices in more detail through hand drawings and digital models. The hybridization of media at this stage was intentional as it sought to construct a density of features and specs that could incorporate the fictional narrative of the original projects. The process involved feedback between the speculative designs and the associated fictional narratives, which allowed proposed features to be shaped and enabled functions to be inferred from representations.

Finally, the elaboration of the fictional technical documentation (blueprints) of the devices belonging to each project was requested. This implied the use of semiotic strategies associated with the technical representations of mechanisms and machines, which are the ones that grant verisimilitude from the social and disciplinary imaginaries they summon. The use of irony and anachronisms (retro) allowed us to distance ourselves from the pseudo-objectivity proposed by the classical technical representations by using Monge geometry (plans, sections, axonometric and exploded views) to transform the design exercise and its representation into a critical operation.

The final results showed a great diversity of approaches but demonstrated that all had managed to critically reflect on human-device interactions and their relationship with urban spaces. We also verified the use of the theoretical and methodological tools suggested, as well as the awareness of the particularities that these interactions have in geopolitically subaltern countries, particularly in Latin America.

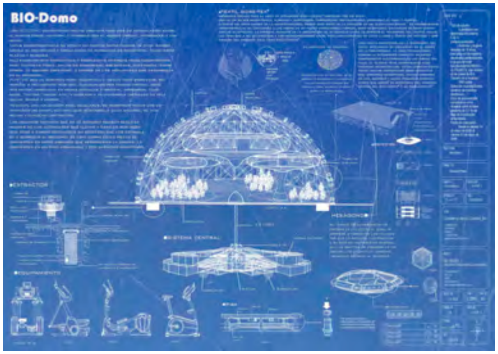

Figure 4
Image by Cucho_Demousselle_Diaz_Escobar_Fazio_Ferreyra_Gonzalez_-Kassis_Sarmiento (UBA)

In terms of a contribution and/or step forward to bring DSLB to fruition, this workshop has created a reservoir of connections between the interpretations about data's presence in the street -as produced in the first workshop- and possible physical artifacts and urban scenes in which they are condensed and appear as operating presences. The outcome is a gallery or palette of elements, aesthetic associations, ways of communicating feasibility and possible operational protocols in the street, that are now available for new recipes that will merge in the other lines of work the project is involved.

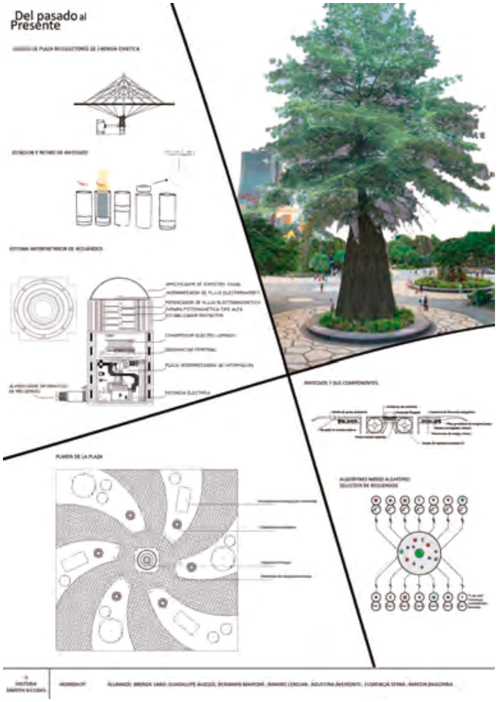

Figure 5
Image by Saad_Auzqui_Marione_Lencian_-Aversente_Serra_-Baigorria (UBA)

These two pedagogical experiences described above show disruptive and provocative ways of approaching from design, architecture, and urbanism to the issues involving the "new media", hyperconnectivity, human-machine interfaces, social networks and the transformation of spaces of public and private life. They also allow us to think about these increasingly pressing problems regarding possible, probable or desirable futures, using speculative and fictional design to critically delve into the utopian, dystopian or protopian visions of the future.

Many questions remain open and we do not intend to draw general or generalizable conclusions from these exercises. We simply want to offer the account of these experiences in order to make it possible to replicate them in other contexts, with other contextual and material conditions, in order to promote the proliferation of works that reflect in a propositional and critical way on subjects that seem distant from the concrete practices of designers and architects, but that are increasingly urgent if we are concerned about our present and future human condition.

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Artistic computational design featuring imprecision

A method supporting digital and physical explorations of esthetic features in robotic single-point incremental forming of polymer sheets

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Design strategies that employ digital and material imprecision to achieve esthetic innovation exhibit high potential to transform the current precision-oriented practices of computation and digital fabrication in architecture. However, such strategies are still in their infancy. We present a design method facilitating intentionally-imprecise esthetic explorations within the framework of digital design and robotic single-point incremental forming. Our method gives access to the esthetic fine-tuning of molds from which architectural objects are cast. Semi-precise computational operations of extending, limiting, deepening and shallowing the geometrical deformations of the mold through robot toolpath fine-tuning are enabled by a digital toolkit featuring parametric modeling, surface curvature analyses, photogrammetry, digital photography and bitmap image retouching and painting. Our method demonstrates the shift of focus from geometric accuracy and control of material behaviors towards intentionally-imprecise digital explorations that yield novel esthetic features of architectural designs. By demonstrating the results of applying our method in the context of an exploration-driven design process, we argue that imprecision can be equally valid to accuracy, opening a vast, excitingly unknown territory for material-mediated esthetic explorations within digital fabrication. Such explorations can interestingly alter the esthetic canons and computational design methods of digital architecture in the nearest future.

Keywords: *Artistic architectural design, artistic digital crafting, creative robotics, material agency, fabrication inaccuracies, robotic single-point incremental forming of polymers*

BACKGROUND

High precision of the digital process and its physical result has been the main target of mainstream computational design research and practice in architecture. The majority of the work focused on developing computational means of simulation, prediction and real-time monitoring of material behaviors during fabrication (Menges 2015; Sheil 2014), to derive physical results that are as close as possible to digital model representations.

Recently, however, a different approach has been proposed; one that purposefully introduces imprecision into the computational process to obtain designs whose infidelity is an esthetic virtue. Single research efforts appeared in this context, such as the studies in experimental 3D printing that explore intentional tweaking of the process to produce erroneous esthetic features in the printed objects (Atwood 2012; Gürsoy 2018; Mohite, Kochneva and Kotnik 2017). Most lately, a more collective effort to advance knowledge has been the ACADIA 2018 conference, featuring the theme: "Recalibration: On Imprecision and Infidelity".

The conference chairs, in a series of manifestoes, advocated that being deliberately imprecise in computation can lead to inspiring advances in architectural esthetics (Kobayashi & Slocum, 2018). More specifically, that intentionally-flawed digital processes, such as glitching, messy programming, simplified iteration, trial and error- and chance-based operations, can yield new typologies of form, surface and texture (Anzalone, Del Signore and Wit 2018a). The chairs also argued that such digital design approaches, repositioning computational design at the intersection of art and technology, can renew the interest of architects in more spontaneous artistic practices, liberated from the convention of ultimate precision (Anzalone, Del Signore and Wit 2018b).

Despite its potential to revive the mainstream practices of computational design and digital fabrication, this strand of research is still in its infancy, as indicated by a low number of publications on the subject. The first steps to advance knowledge have been taken, but a fully established generation of novel digital design practices celebrating imprecision is yet to emerge. In light of this challenge, this research study contributes with a digital design method deliberately featuring imprecision to facilitate esthetic explorations of emergent design features in a fabrication process of robotic single-point incremental forming (SPIF).

STATE OF ARCHITECTURAL RESEARCH ON ROBOTIC SPIF

Extending the role of imprecision in robotic SPIF is important from the standpoint of knowledge advances in digital fabrication in architecture. Firstly, because research so far has been focused on developing methods that increase precision and geometric accuracy (Kalo and Newsum 2014; Nicholas et al. 2016). To our knowledge, no published methods exist that engage with the inaccuracies in SPIF for creative, esthetic purposes. Only one study briefly mentioned that the imperfections in the form of microcracking of incrementally formed polymer elements could be an interesting design generator (Lublasser et al. 2016). However, this remark was not further elaborated on in the mentioned study due to a different research focus.

The second reason motivating our research relates to the scope of knowledge on materials used in architectural SPIF. So far, the majority of studies have focused on SPIF of metal sheets while knowledge on architectural forming of polymers is limited. SPIF of polymers is interesting from the imprecision standpoint due to their lower stiffness in comparison with metals, which results in a potentially wider range of imperfections occurring in the formed object (Franzen et al. 2008). New studies are therefore needed which explore how this higher degree of forming inaccuracy affects the esthetic exploration potentials.

Thirdly, the previous research on architectural SPIF embraced its employment to produce smaller architectural elements, assembled to form larger structures, such as façades, roofs or flooring (Kalo and

Newsum 2014; Nicholas et al. 2016). New studies are needed that explore other architectural applications of SPIF, such as in the production of molds used for casting architectural elements from other materials.

RESEARCH CHALLENGE AND AIMS

Prompted by the above challenges within the current state of the art, we set out to determine how the traditionally precision-focused computational design process can accommodate imprecision to enable deliberately inaccurate explorations of esthetic features arising from the inaccuracies of the SPIF process. The introduction of deliberate inaccuracy into the process was driven by design-oriented premises. Our goal was to demonstrate the positive effects of allowing partially unpredictable material behaviors to affect the esthetic appearance of the final design.

To reach this goal, we established the following research aims. Firstly, to compose a set of digital media enabling computational design explorations featuring imprecision and intuitive artistic design explorations. Secondly, to develop visual programming scripts allowing for intentionally-imprecise modifications of object geometries for the purpose of creative explorations of geometric inaccuracies of polymer sheet SPIF carried out using a robot. Thirdly, to provide an example of a design object whose features are iterated using our method and to discuss the esthetic implications of our method application.

RESEARCH METHODOLOGY AND DESIGN

Our research design combined the elements of artistic architectural research (Dyrssén 2011) and architectural research-through-design (Dunin-Woyseth and Nilsson 2008). Such a duality enabled us to devise a custom research workflow based on a hybrid mode of investigation. We deliberately combined unrestricted, speculative artistic creation activities, geared towards exploring the fundamental esthetic aspects of design, with more rigorous research activities, taking the form of carefully designed architectural experiments involving computational design and robotic SPIF.

Our investigation started with the construction of a hypothetical design workflow and a set of digital techniques enabling its execution. The workflow and toolset were derived based on the results of our previous research involving the robotic SPIF process. Next, we validated this hypothetical workflow by carrying out a series of iterative design experiments that followed the steps of the workflow and that employed its accompanying digital toolset. Here, we devised three design cycles embracing intentionally-imprecise alterations of geometrical input and carrying out the SPIF process for each of these alterations. As these cycles proceeded, we were analyzing the suitability of the respective steps of the workflow and the enabling toolset for carrying out artistic explorations of geometric inaccuracies of SPIF. Having continuously refined our assumptions in the course of our experiments, we arrived at the final workflow and digital toolset suitable for implementation in esthetic exploration-oriented architectural design.

THE METHOD SUPPORTING ARTISTIC EXPLORATIONS IN ROBOTIC SPIF

Our proposal embraces a computational design method facilitating intentionally-imprecise explorations of esthetic variations of a design object's geometry materialized using robotic SPIF. The method gives access to the fine-tuning of polymer mold geometry from which architectural prototypes are cast. When formed incrementally, the mold undergoes unanticipated deformations due to internal strains induced by the forming process. Some areas sink down, while others are pushed upwards. These deformations result in local convexities and concavities that cause the physical outcome to differ locally from the silhouette of its digital original.

Moreover, the geometrical 'errors' of the mold cause the liquid silicone, cast into the mold, to accumulate in thicker layers around the convex regions and to become thinner in the concave ones. This varied silicone-settling culminates in color intensity and surface translucency increases and decreases, spread across the silicone cast. These optical effects comprise emergent aesthetic qualities added to the cast object, unanticipated and not designed from the beginning but interesting from the esthetic standpoint.

Our method also allows the designer to further explore these emergent esthetic qualities and through such explorations generate variations of the original design by tweaking the shapes, locations and sizes of silicone accumulation and thinning zones. In particular, the method gives access to the esthetic fine-tuning operations of extending, limiting, deepening and shallowing the mold deformations in chosen areas through semi-precise robot toolpath fine-tuning.

The digital toolset enabling such explorations combines parametric modeling, digital surface curvature analyses, digital photography, painted bitmap image creation and photogrammetry. The geometrical and numerical data produced with these tools are used as input for the exploration-oriented iterative computational design workflow, accessed through a custom-developed visual programming script. The script facilitates an iterative generation of mold geometry variations. Such variations affect the silicone settling patterns in the physical pieces.

The script allows the designer to demarcate the zones of the original digital surface that shall undergo fine-tuning. Further, it provides visual and numerical control of the scope and amount of applied geometrical change. Although employing computational means, in several points it is intended to accept input from less precise operations, such as freehand bitmap painting and arbitrary geometry depth adjustments. Additional moments of subjectivity and inaccuracy can also occur in setting the patch surface generation parameters, when determining mesh density, during the sampling of bitmap paint strokes onto the affected geometry points and when setting the parameters for mesh smoothing.

Our method is intended both for generating design objects that belong to pure art as well as for artistically developing the esthetic features of objects that are architectural, such as ornamental facade panels, decorative interior elements etc. The average dimensions of a bounding box of the elements produced in this study was H68 x W92 x D18 cm. The size of such molds produced using the industrial robot arm technology could probably be much larger and reach interior room or building façade dimensions. The maximum sizing will depend not only on the robot arm reach but also on a combination of other factors, important from the standpoint of the incremental forming process. Such factors include the individual geometrical deformations inherent for particular geometrical designs, strength and location of dynamic springback occurring during forming, forming angle, forming tool diameter, polymer sheet thickness, maximum material frame and backing plate sizing possible to manufacture and effectively support the material sheet etc. Extensive research is needed to further explore these scaling up aspects and determine the dimensional limits of polymer sheet SPIF.

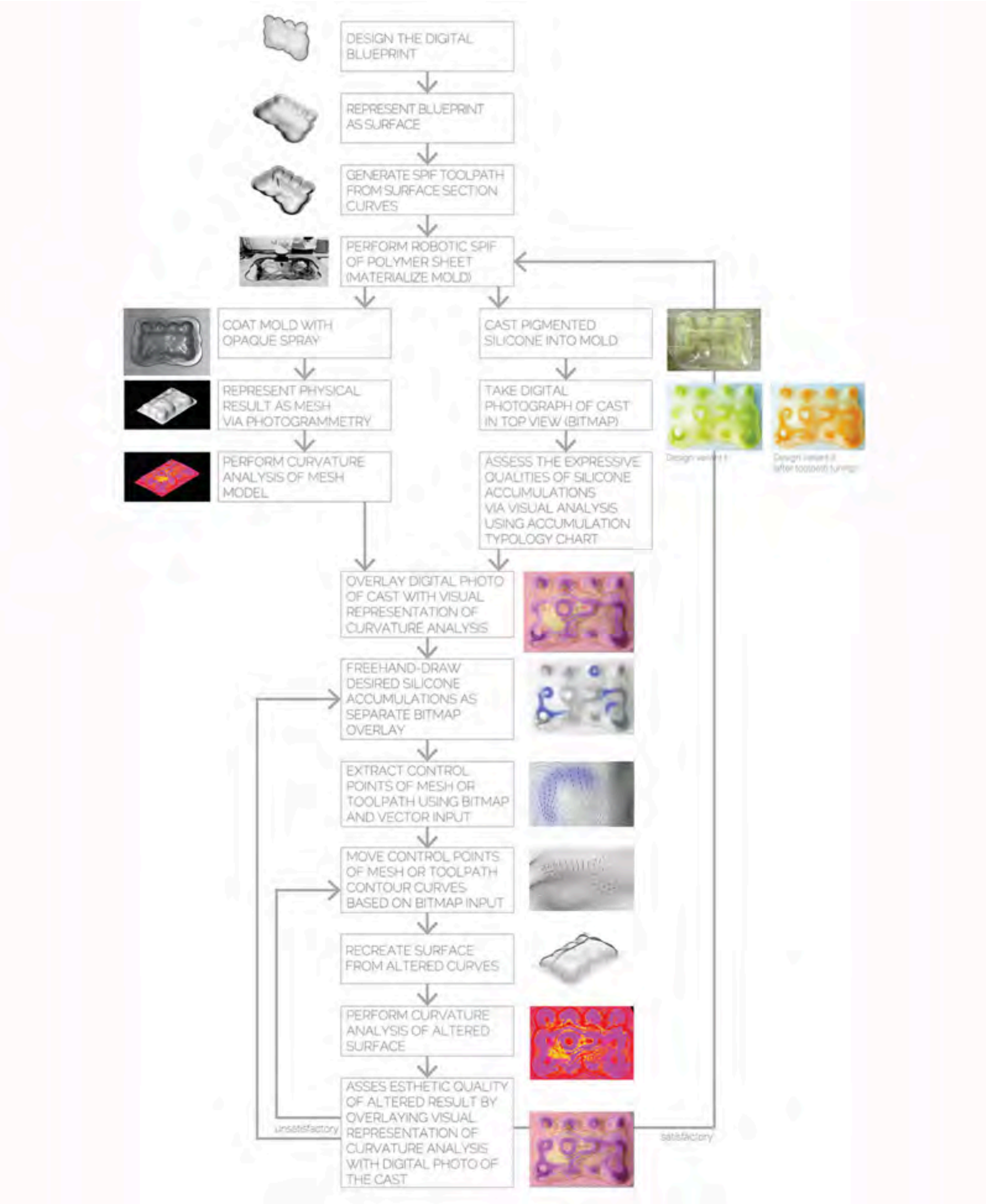
METHOD IMPLEMENTATION

To provide an understanding of our method implementation in the context of artistic explorations featuring imprecision, below we give an account of the first two design phases, encompassing design generation and the first geometry fine-tuning cycle. The steps of the design workflow accompanying such a fine-tuning cycle are also shown in Figure 1.

The explorations were carried out with the support of the two custom visual programming scripts facilitating the implementation of our method. The architectural purpose of the design objects produced in this study is related to the development of novel expressions for tangible interactive architectural interfaces, described in more detail in another publication (Zboinska, Dumitrescu & Landin, 2019).

Our exploration began with designing a digital object serving as a blueprint for the esthetic exploration process. By means of visual programming, we created a parametric metaball system outputting section curves that approximated the outline of our design object. The curves were then split in half along the longitudinal axis of the geometry to create

Figure 1
The iterative computational design workflow deliberately featuring imprecision to enable esthetic design explorations.



two assemblies, representing two mirrored sides of our object.

Next, one of the two symmetrical curve assemblies was used to generate a patch surface. To satisfy the needs of the SPIF process, that patch was rotated to a horizontal position and an outskirt surface was added at its border for improved formability. The patch and outskirt were then intersected with a set of cutting planes to obtain planar section curves. These curves underwent a series of parametric transformations, leading to the construction of a single polyline toolpath, legitimate for the robotic SPIF process. Finally, robot code for toolpath execution was generated and the first SPIF process was carried out using the code. Liquid pigmented silicone was then cast into the formed mold, yielding the first physical design instance.

Ocular comparisons between the digital blueprint, the physical mold and the silicone cast revealed the discrepancies between them. The major inaccuracies of interest for this study occurred at the originally convex areas of the digital blueprint. As shown in Figure 2, in the physical mold these areas became inverted, forming local concavities, which in the silicone cast presented themselves as local thinning and thickening of the cast material.

These unexpected local silicone accumulations caused by unplanned mold deformations inspired the workflow in the first cycle of digital geometry fine-tuning. We started by taking a top-view digital photo of the silicone cast. We also performed photogrammetry of the mold, to obtain its digital 3D mesh representation. With this step, we introduced the first moment of intentional inaccuracy, by choosing a less exact method of photogrammetry instead of ultra-precise 3D scanning for generating the digital representation of the mold. The aim was to generate a fine discrepancy between the physical result and its digital representation and to employ that intentionally less precise digital representation as input for design fine-tuning. The overall intention was to explore how this would affect the geometry of the next physical design iteration.

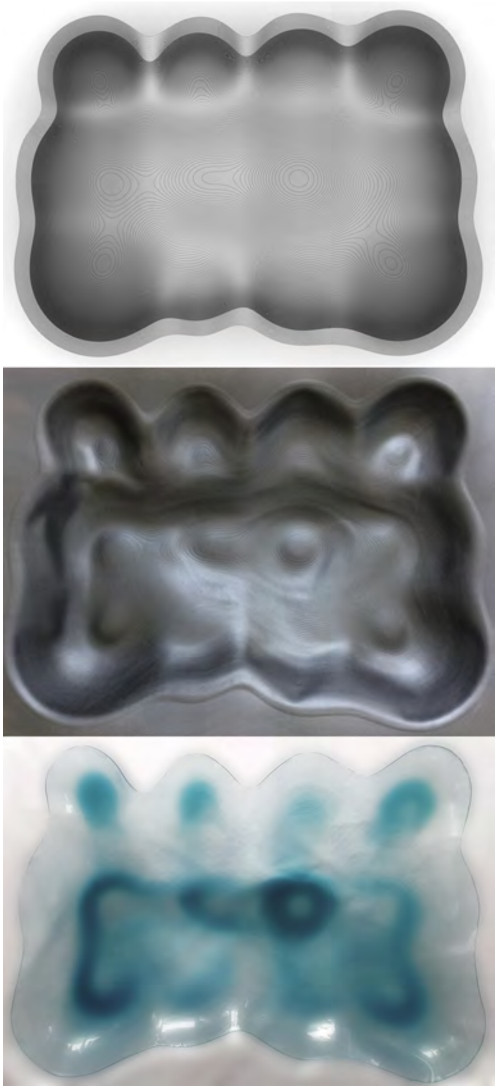


Figure 2
A comparison between the original digital input shape (top), the local geometrical deformations of the polymer mold (middle, coated for the purpose of photographing) and the resultant material accumulations in the silicone cast (bottom).

Having the mold represented in digital form, we then carried out a computational analysis of its mean curvature. The result was a false-color illustration visually reinforcing the locations of concave and convex zones in the mesh. Next, in a bitmap editing environment, we overlaid the images the silicone cast and the mesh curvature analysis. We then used them as guides for the process of less accurately and more casually painting the desired new silicone accumulation zones. These were painted instinctively by hand, using a series of digital brushstrokes, created in a separate drawing layer on top of the underlays. Upon the completion of this step, we saved a bitmap representation of the painted zones in an image file format. Additionally, we extracted the boundaries of the painted zones as curves in vector format.

The next phase encompassed importing the bitmap and the boundary curves representing the painted zones as inputs for our visual programming script. Using these two inputs, we then extracted and selected the vertices of the photogrammetry-derived 3D mesh to be affected by fine-tuning. The fine-tuning took place by moving the mesh vertices in the Z-direction by values generated based on color brightness sampling performed for the bitmap image representing the previously painted silicone accumulation zones. For a more arbitrary and imprecise effect, we introduced a multiplier for the movement values and an additional sine graph for remapping them.

In the final phase of the digital design cycle, we visually evaluated our final version of mesh point movement with the aid of a mesh curvature analysis for the altered mesh. Having assessed the result as esthetically-satisfying, we introduced another moment of inaccuracy, by subjecting the mesh to a process of smoothing after the move of the vertices, to achieve softer transitions between the fine-tuned and the unaffected mesh areas.

Our process continued towards completion with the contouring of the fine-tuned mesh in the 3D modeling environment. The planar curves resulting from the contouring became a basis for the construction of a new patch surface. That surface was used as an underlay for generating a robot toolpath and its execution program, using our second visual programming script. The program was then ran on the robot as the second SPIF process. Ultimately, silicone was cast into the robotically-formed mold, generating the first iteration of our design.

Having the physical result of this first iteration, we repeated the cycle of digital and computational fine-tuning, according to the workflow described above. For this second design iteration cycle, we also used the 3D representation of the second mold geometry generated via photogrammetry as input, to iteratively transform our design.

ESTHETIC IMPLICATIONS OF THE METHOD

Figure 3 illustrates the geometrical differences between the three molds produced using the intentionally-imprecise digital geometry and robot toolpath fine-tuning. Figure 4 shows the effects of the fine-tuning in the final design objects, appearing as varying silicone accumulations. Interestingly, accumulation shape typologies such as an island, an atoll and a lagoon emerged as a result of the fine-tuning. From the design conceptualization standpoint, such typologies can form a catalog of esthetic forms representing a formal vocabulary underpinning the fine-tuning of the first design. Such a catalog can become a point of departure for further playful explorations that either develop and reinforce the derived accumulation typologies, or strive to obtain new ones.

In addition, the esthetic result presents other features potentially original from the standpoint of architectural materiality. The first of those features encompasses the optical effects of seamless color and transparency transitions taking place within one material entity. These offer opportunities for further esthetic design development, such as explorations of transparent color overlays within a single architectural mass.

A second new feature relates to the tactile qualities of the resultant design object. The variations in material thickness and distribution cause variations in the stiffness and thickness of the silicone cast. The object mass seamlessly morphs from thin to thick and from soft to stiff across the object surface, with no sharp property changes in-between. Additionally, as shown in Figure 5, the line-work following the path of the tool from the forming process is captured within the cast, forming an inherent detail with an unusual optical effect and tactile potential.

These features bring in esthetic qualities that can mediate a novel visuo-tacile experience of architectural materiality, achieved through an unconventional treatment of architectural material as a voluminous substance designed to convey bulk, thickness and texture. Moreover, the scalability potential of the robotic forming process suggests that objects such as the ones presented in our study could easily become walls, floors and ceilings, cast as single, monocoque pieces that enrich the experience of architectural space through their exotic materiality.

REFLECTIONS ON METHOD APPLICATION

The key strength of our method is that it enables creators to explore design iterations in a hybrid mode, combining more spontaneous artistic activities with operations based on computational logic. It provides high levels of expressive freedom at the intentionally-imprecise moments of the design process, while also exploiting the capacities of computation to facilitate materialization of geometrically-complex designs. It also offers the possibility to benefit from the imprecision of the fabricated object by using it as a catalyst for esthetic explorations.

One of the main challenges of using our method is that it demands a deep understanding of the material behaviors accompanying the incremental forming process. It also requires fundamental knowledge on other types of forming inaccuracies that affect the geometrical deformations studied herein, accompanied by a thorough comprehension of the relationships between the material behaviors, the particular shape of the formed geometry and the process requirements.

The application of our method also involves a risk of failure upon each iteration run due to the high unpredictability of the dynamic springback occurring upon forming that may cause material breakage.

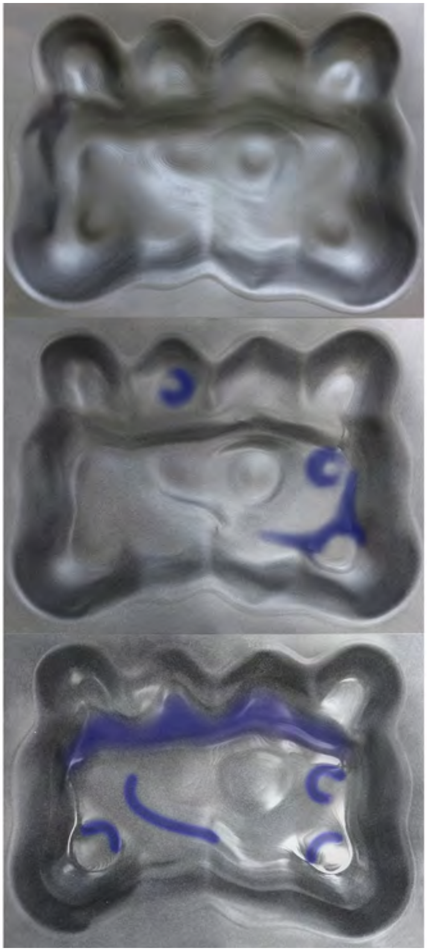


Figure 3
A comparison between three polymer mold geometries created with the aid our method (coated for the purpose of photographing and accurate illustration of geometrical differences). The top mold is the first design while the middle and bottom molds are its iterations. The location of digital paint strokes used as a basis for the intentionally-imprecise computational toolpath fine-tuning is indicated in blue.

The effect is highly dependent on input geometry size, shape, local curvatures and the nature of their transitions. As our experience with the process reveals, even a small alteration in the shape and curvature of the input geometry may cause the process to fail. Therefore, some designs may be possible to fabricate, while others may not. Without additional digital simulation aids it is difficult to predict which will be the case without carrying out the forming process.

Figure 4
Three design iterations, featuring differing silicone accumulations, obtained owing to the application of our method in the exploration process.

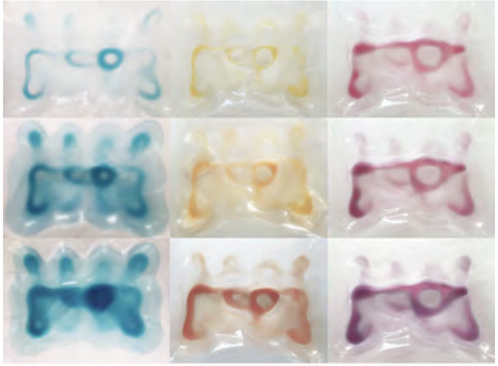


Figure 5
Original esthetic qualities, embracing inherent textural properties, unusual transparent color transitions and unconventional volume treatment featuring varying thickness and stiffness of the architectural material within one mass, all arising from the application of our method in the design process.

To implement our method in the creative industry and the building sector, extensive further research is hence needed that aims to develop architect-friendly computational simulations of dynamic material behaviors occurring during forming and indicate which geometries are feasible for successful SPIF processes. Such interdisciplinary research needs to take place at the intersection of architecture, manufacturing and material engineering.

CONCLUDING REMARKS

With the results of this study, we contributed to the broadening of the existing knowledge on the forming of polymers for architectural purposes. We analyzed how the geometric imperfections inherent to the forming of this material can be generative in shaping the esthetic expression of the formed object. Inspired by the need to explore unfamiliar architectural applications of SPIF, we also provided an example of a novel utilization of SPIF to produce molds for casting single non-panelized architectural pieces from a liquid material.

Our study yielded a method of digital design that transforms the fabrication inaccuracies from unwanted annoyances to desired, intrinsic features of the design that can be explored as esthetic variations. We promoted working intuitively and in a deliberately imprecise manner within a computational environment, while also ensuring that the design results from our process are relevant and novel from the esthetic standpoint. Our account of the method implementation demonstrated how the designer can shift focus from ultimate control of material behavior and geometric accuracy towards unrestrained digital explorations of the novel esthetics of imprecision. Through this, we have shown that it is possible to transform the limitations of tools and materials into virtues, providing opportunities to innovate at the artistic level of design.

Our method allows for the viewing of computational design from a refreshing perspective, marked by curiosity-driven explorations of computational processes and their influence on unpredictable material behaviors. We hope it will play a role in promoting further advances in the research, education and practice of creative architectural robotics. The provision of such new methods is intended to inspire the development of other approaches to handling inaccuracy for esthetic design purposes in architecture. Such approaches will be crucial for rejuvenating interest in artistic, liberal and spontaneous ways of creation within architectural computation.

Ultimately, we hope to have demonstrated that in the age of the fourth industrial revolution, which we believe is a revolution of digital creativity, the application of digital technologies does not need to fixate on the production of accurate designs only. Positioning imprecision as a design prerequisite that is as valid as accuracy opens a vast, excitingly unknown territory of design explorations that can interestingly alter the image and perception of contemporary architecture. Architectural objects can authentically reflect the nature of the imperfect processes behind their becoming. This fact lays the foundations for the emergence of new paradigms in expressing the materiality of tomorrow's digital architecture.

ACKNOWLEDGMENTS

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Speed of Deposition

Vehicle for structural and aesthetic expression in CAM

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This paper presents intermediate results of an experimental research directed towards development of a method that uses additive manufacturing technology as a generative agent in architectural design process. The primary technique is to variate speed of material deposition of a 3D printer in order to produce undetermined textural effects. These effects demonstrate local variation of material distribution, which is treated as a consequence of interaction between machining parameters and material properties. Current stage of inquiry is concerned with studying the impact of these textural artefacts on structure. Experiments demonstrate that manipulating distribution of matter locally results in more optimal structural performance, it solves printability issues of overhanging geometry without the need for additional supports and provides variation to the surface. The research suggests aesthetic and structural benefits of applying the developed method for mass-customized fabrication. It questions the linear thinking that is predominant in the field of 3D printing and provides an approach that articulates interaction between digital and material logics as it directs the formation of an object that is informed by both.

Keywords: *digital fabrication, digital craft, texture, ceramic 3D printing*

INTRODUCTION

This paper presents intermediate results of ongoing research directed towards devising methodology on utilizing 3D printer as a generative element of design process. The overarching thesis is that manipulation of fabrication parameters leads to various architectural facets being informed by the process of making. The objective is to develop a rigorous system for materializing interdependencies between geometry, material, machining instructions and physical forces.

The project started with series of experiments on adding and subtracting mass from basic, hollow cylinder by manipulating deposition speed of a 3D printer. The faster printer moves the less matter it deposits. In order to render that simple principle operational, a system of multiple speed gradients arranged in rhythmic sequences was devised in G-code. The suggested method of printing creates webbing and looping, weaving and knotting ornamental expressions. To design the relationship between the speed

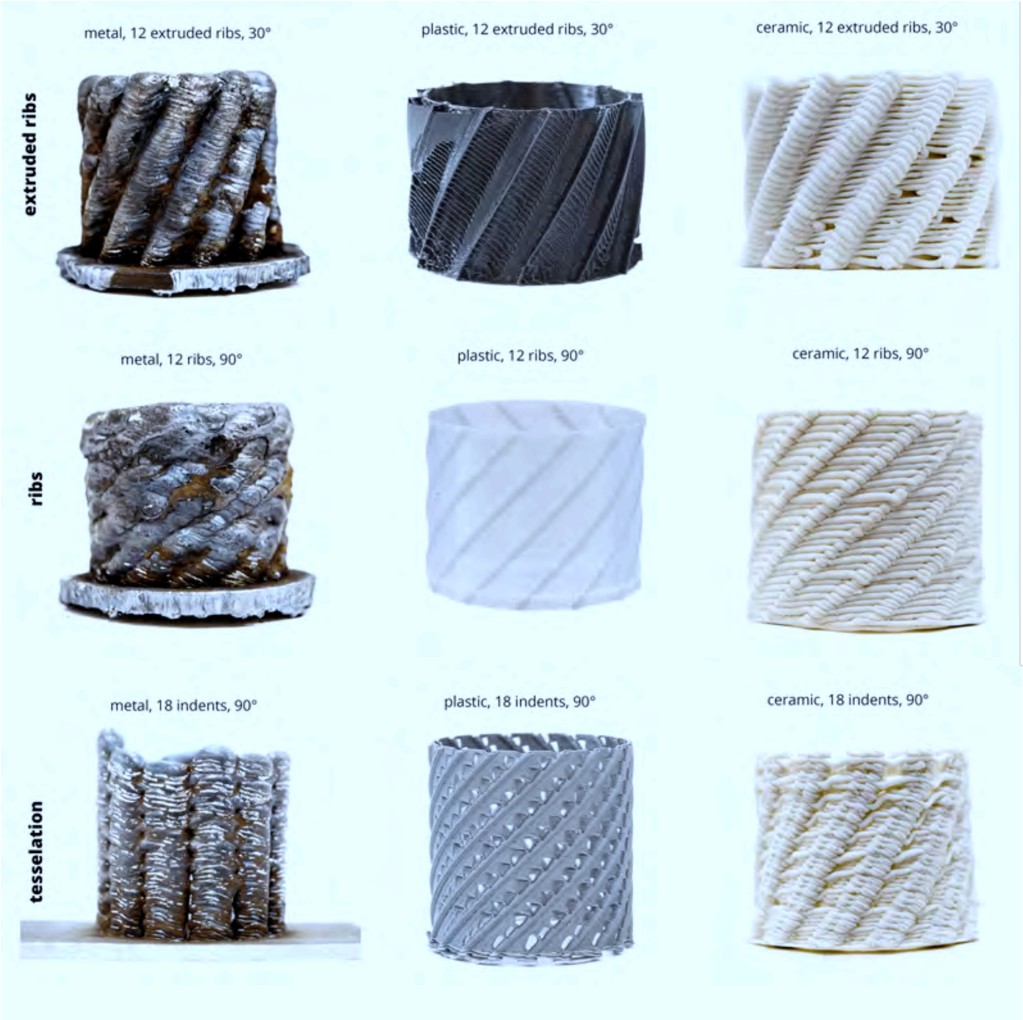

Figure 1
Materiality studies

of deposition and a material is to design time contingent, controlled variation of semi-ornamental mass distribution at the surface scale and beyond. Series of experiments on role of materiality in the method suggested that these textural formations may have structural implications. Slower speed can, for example, contribute to fortification of weaker points of the structure, looping and webbing excess provide a way to carry following cantilever layers without the need for additional supports. Larger surface area of the connections between layers leads to increase in structural integrity. This paper presents the work done on determining how exactly undesignable texturization can be both an expression of tectonic forces operating in a model and a field of reinforcement and stabilization.

RESEARCH CONTEXT

Research attempts to build upon recent projects that explore unexpected and innovative ways of practising digital manufacturing (Atwood 2012) as indeterminate translation of G-code through a specific matter. Drawing partly from the concept of digital materiality (Gramazio and Kohler 2008), partly from the work on material computation (Fleischmann and Menges 2012) , such approach implies the design of how numerical input is processed through a materiality constituted by properties and behaviours. In case of the project described here, that approach results in emergence of textural effects, semi-controlled formations; effectively a by-product of interaction between material and fabrication. Stringing, which is commonly perceived as erroneous side effect of unskilled design of a G-code, is encouraged in this case by intentional modification of production parameters. That subversive technique owes its theoretical base to the discourse on craft in digital fabrication. “Misuse” of the machine converts the space of making into space of discovery (Kolarevic 2008). Discovery implies an element of risk, therefore the process is continuously concerned with producing an outcome that falls within a pre-specified range, determined by certain criteria (Pye 1968). Value of indeterminacy, error, glitch and deviation resides in questioning the use of CAM as a linear sequence meant to engender continuous variation, a process that merely extends industrial mass production (Perez 2017). Digital craftsman’s project is to design the interaction between digital and material logics (Gramazio and Kohler 2008) by building a system that directs how material is going to be shaped in a specific fabrication environment and allowing material to affect the outcome (Satterfield and Schwackhamer 2017) .

PREVIOUS EXPERIMENTS AND METHOD

Multiple series of hollow cylinders in three different materials (plastic, ceramic, metal) were printed using ribbing and tessellation as patterning techniques (Figure 1). Corresponding models in each of material sets were produced with the same machining setup. Accumulating or shedding mass through ribbing or tessellation requires a specific toolpath augmented by a pattern of deposition speed. The essence of the approach is to design how fast or slow or not at all printer moves in certain locations of the toolpath, how and when it accelerates, how fast does it come to a standstill. It is a temporal process augmented by materiality (Cohen 2018). Fundamentally, the framework of experimentation consists of four main agents: geometry, fabrication, material and physical forces (currently, gravity plays an important role); each of the agents in the system has a set of parameters, some are used as variables, some as constants; behavior of each agent is informed by others. Three groups of models, which have matching digital geometry and same manufacturing instructions, diverge significantly not only in the local geometry of resulting patterns, but in the nature of overall effects that they produce. Correlating models in all three materials were compared and studied to understand the difference and its possible causes. Results (Mohite et al. 2018) led us to believe that textural formations could play a structural role because adding and removing mass from an object necessarily affects its tectonic performance.

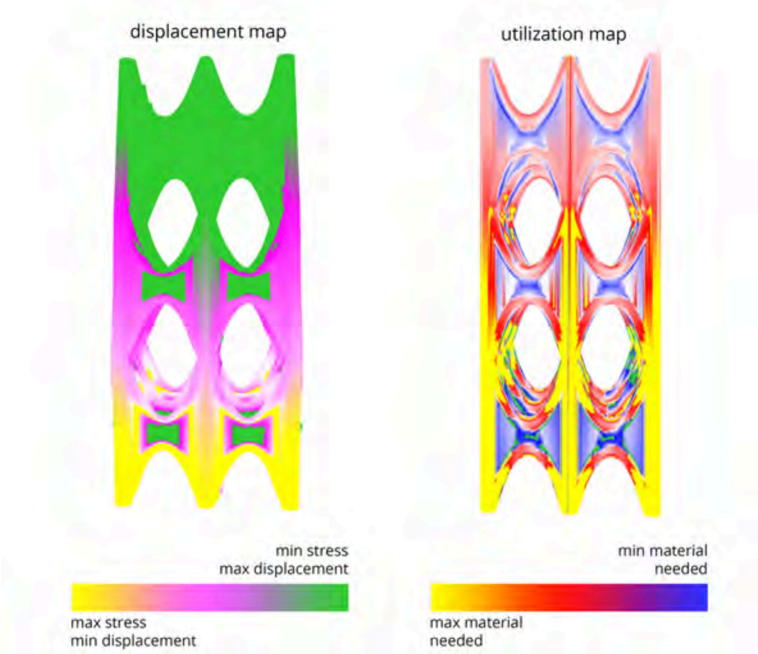

Figure 2
Utilization and displacement map in Karamba3D

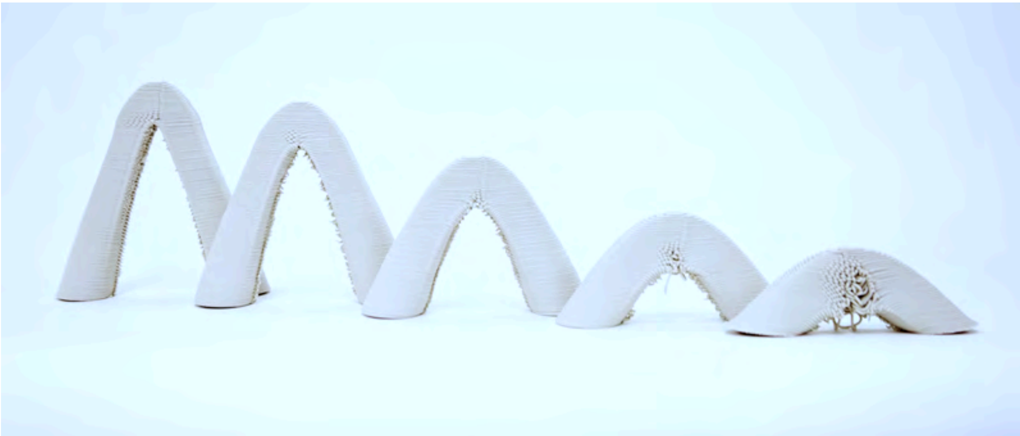

Figure 3
progression of arches from three-pointed arch to round arch to determine the geometry with most severe printability issues

PROCESS

Current project started with determining three main tasks to accomplish by employing our method:

- to print a relatively large structure with cantilever geometry without additional supports.
- to resolve structural problems that arise from self-weight and geometry.
- to provide textural variation, which is governed by tectonic forces acting in the model.

A large lattice structure, consisting of a 3-D system of 16 arches was designed to be printed. Displacement and utilization structural analyses were carried out in Karamba3D (Figure 2). Displacement map shows the distribution of stress in the shell and allows to understand where tension, compression and lateral stress occur. Utilization map demonstrates how much matter any given area of the model needs to be structurally sound. Studying both maps revealed the necessity of testing different areas of the model before printing it. Three main structural cases were discovered within the model, and it was decided to test them individually to ensure the successful production of the large model. To address these cases three models were designed to be printed with and without textural treatment. Due to time constraints, this paper presents only that preparatory work, however, these intermediate results clearly demonstrate ornamental and structural performance of speed modulation technique.

The process started with finding out which arch cannot be printed without supports as one of the goals was to demonstrate how using speed variation method can improve printability of cantilever geometry. A progression of arches from three-pointed arch to round arch was produced. It was decided to work with an arch, which when printed without speed variation fails in that a hole at the top section of the arch is large enough to instigate structural collapse (Figure 3).

Models are printed in ceramic because of larger layer height, which complicates printing of cantilever geometry. Material studies were carried out to determine the ceramic mixture, which, on the one hand is ductile enough to allow stringing and, on the other hand, is solid enough to not break down due to excessive flowability. The final ceramic composite contained 50% kaolin, 25% feldspar, 25% quartz, to which following elements were added: 33% water, 0.5% bentonite. Ceramic is a material that undergoes several phase transitions. First, it is in viscous liquid state, then it dries naturally and then it is fired in a kiln. That means that as it dries naturally the moisture level in the model has to be continuously controlled to prevent rapid drying, otherwise cracks will appear. In a kiln it significantly shrinks, so for all the models a special base was designed so that it contracts with the model avoiding the deformation in the lower part.

The analysis of displacement and utilization maps of the large model showed that there are three main structural cases (Figure 4):

- top area, where geometry has minimal load and therefore needs least amount of material, however it is most susceptible to lateral stress and therefore deformation.
- middle area, where two different printability issues occur due to cantilever geometry. Also that area experiences lateral stress and tension.
- bottom area, which is in compression and needs most amount of the material to support the weight from above.

Based on that, three models were designed to structurally mimic the behavior of the described cases (Figure 4). They were printed without applying texturing technique. As was expected, the model representing the top section was subject to lateral stress, which produced bending (Figure 5). The model representing the middle section has failed because of lateral stress in cantilever geometry; excessive deformation rendered the model unprintable (Figure 6). The third model, while also demonstrating extensive printability problems, shows bending in its lower section, because the mass is insufficient to support the structure (Figure 7).

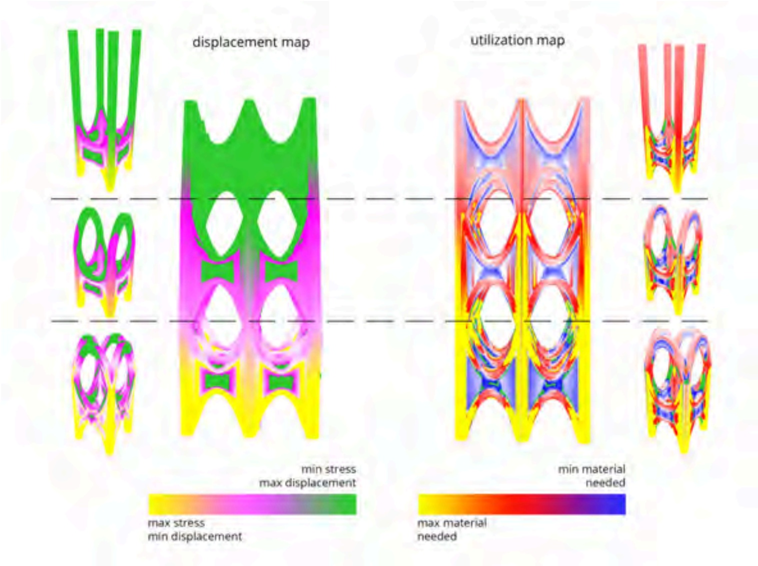

Figure 4
Displacement and utilization maps of large model and three corresponding models.

The strategy for designing textural effects in G-code uses displacement and utilization maps as its foundation. It was decided to employ extruded ribs as main texturization technique. In some areas they are directed outwards and in some inwards. Inward ribs are mainly used to improve printability by connecting the walls that surround cantilever geometry. They are also utilized in the areas that are under minimal compression and are highly susceptible to deformation. The density of ribs depends on utilization map, directionality and length of extrusion depend on displacement map. Maps are exported from Karamba3D as a mesh into Grasshopper. Vertices' RGB values are used as color gradient that drives density and distribution of texture. Three models with effects show how the proposed method of speed variation can alleviate certain structural problems as well as ensure printability of overhanging and unsupported arch geometry (figure 8,9,10). A field of knotting and looping formations accumulates mass where it is needed and provides structural reinforcement for areas under lateral stress. As the method is focused on working with speed of deposition and

Figure 5
Model printed without effects under lateral stress

Figure 6
Model printed without effects. Two cases of printability issues and lateral stress

Figure 7
Model printed without effects under compression.

Figure 8
Model printed with effects under lateral stress

toolpath instead of manipulating actual geometry, the process of fabrication itself is designed, which ensures continuous local variation and at the same time repeatability of results. Textural artefacts are produced as an extra layer of embodiment of communication between fabrication and materiality. Patterns and effects illustrate structural tension and compression, the path and speed of a printer and behavior of composite paste. It is a materialized trace of making, not a designed shape (Cache 2004). Presented approach to 3D printing allows texture to play both ornamental and structural roles. It is not plastered on the object indiscriminately, instead, texture becomes an agent of translation of machine logic into material logic. The aim of the research is to understand and methodize affordances and constraints of a dynamic system of formation. Through persistent experimentation with patterns of semi-controlled material distribution, we hope to enrich the practice of 3D printing with the instrumentality to craft surface ornamentation as trace of structuring informed by a specific material.

RESULTS

An established way to utilize a 3-D printer is to produce precise and predictable products, which geometrically match digital models. If customization is desired, it is achieved by creating series of parametrically manipulated digital models that are then printed. In mass construction, even if certain parts or configurations are parametrically customized as digital models, to achieve true variation from object to object is not a straightforward task. Concurrently, designing texture often lies on the margins of design process, it is rarely articulated or employed for anything beyond purely visual effect. However, it can be argued that short-range formal expressions are located in the space of convergence of material and digital logics, which makes texture into a suitable problem for digital craft. Our approach is a step towards devising a simple methodology that allows to feed textural variation directly into the process of making of construction parts based on geometry and

Figure 9
Model printed with effects. Two cases of printability issues and lateral stress

Figure 10
Model printed with effects under compression.

structural needs. With right degree of control, each instance will be slightly different in predetermined locations and in a designed way. That would allow to create 3-D texture on surfaces, reinforce structural elements and ultimately promote heterogeneity in our built environment.

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Anatomy of a Building

Introducing interactive RGB lenses for architectural data visualization

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The paper proposes an alternative way to present architectural information, using color filters - specifically RGB lenses - as an interface to emphasize or reveal the internal structure or hidden logic of an architectural artifact. In an interplay of analogue and digital techniques, it employs rules of color blocking in order to highlight certain aspects of complex buildings, urban plans, or interiors, which cannot be discovered using conventional visualization methods. In this research, the authors developed an interactive RGB lens-interface and techniques for superimposed color visualizations that can be used for an enhanced visualization of the internal structure of a building. By applying physical or digital color lenses, viewers can perceive individual layers of project visualizations, in order to understand certain tectonic or construction logics, such as skin, structure or infrastructure. Based on existing bibliography, the paper presents the workflow from drawing, 3D model or photograph to RGB visualization, through a series of test case scenarios applicable to the field of architecture and design.

Keywords: *architectural visualization, color & light, subtractive color mixing, RGB lenses, post-digital, building anatomy*

INTRODUCTION

RGB visualizations, which reveal themselves only when seen through a color filter, are widely known from artworks, science shows, books (Demois and Godeau 2014) and board games [3]. They often have the form of encoded messages that can be read with the use of decoder glasses, also called magic lenses. When seen in white light and without the glasses, these multi-layered color visualizations often seem chaotic to the viewer. Consisting of layers with superimposed information, they are intentionally confusing to the eye, in order to conceal certain information. Different parts or layers of the images are revealed when the color of the light changes, or when seen through a colored lens. This representational strategy for hiding or revealing information can be applied to different scales - from urban scale to product design - offering an insight into the anatomy of a building or object.

PRECEDENTS IN THE USE OF LENSES FOR VISUALIZATION

There are several precedents of the use of lenses for visualizations. This research draws on different disciplines to investigate this concept in order to find new uses for lenses in visualization, and to extract the knowledge that could be applicable to architecture.

A moveable filter can be applied as a user interface tool that is placed above an image, similar to a magnifying glass. Thereby, the appearance of the objects in that specific region is changed, helping viewers to understand different aspects of visual information (Stone et al. 1994).

Bier et al. researched visual filters, called "Magic Lens" filters, which are transparent or semi-transparent user interface elements "that modify the presentation of application objects to reveal hidden information, to enhance data of interest, or to suppress distracting information" (Bier et al. 1993). These are digital widgets that can be applied to a 3D model, in order to view a selected region of interest as wireframe or magnified, or - in combination - as magnified wireframe.

Depending on their function, some lenses can be used on color as well as on black-and-white images (e.g. magnifying glasses), whereas others can only be used on color images with specific properties (e.g. decoder glasses).

The basic concept of color lenses as filters was developed in the pre-digital era, often referred to as "decoder glasses", where both lenses are the same color (i.e. blue, red), revealing hidden messages when looking through them. Color lenses have also been used to achieve stereoscopic views and anaglyphs, using the well-known - and currently considered "retro" - red/blue glasses, or digital hardware like 3D shutter glasses. To be able to use color filters on images, these images need to have certain properties. The filtering concept may be based on additive or subtractive color mixing (see chapter "How to Build an Architectural RGB Visualization").

Colors are extensively used for visualization purposes, like semantic labeling and remote sensing (Audebert et al. 2017), scientific diagrams with pseudocolor, RGB representations of height maps or physical properties. Oppositely, superimposed color images - with color-coded information or illustrations - are used with the purpose to conceal information, which cannot be understood without decoder glasses.

Milan-based art collective Carnovsky utilizes color filtering of superimposed color images, whose appearance changes when seen in colored light or through a color lens [2]. Carnovsky pioneered shape-shifting RGB art and became famous for their experiments of visual effects of chromatic manipulation, particularly with their exhibition in the Johannsen Gallery in Berlin and their installation at Milan Design Week in 2010. Their projects consist of complex images with superimposed layers in cyan, magenta and yellow, which seem chaotic in white light, but perfectly ordered in red, green or blue light.

The Computer Graphics and Geometry Laboratory of EPFL researches reflective and refractive filters, controlling light by optimizing the geometry of the filter to produce caustic effects in the desired shape (Kiser et al., 2013). They use high contrast color caustics, lighting a piece through a refractive multicolor filter, to achieve a projected image in the color of the original image (Schwartzburg et al. 2014).

APPLICATIONS OF COLOR FILTERS IN ARCHITECTURE

Colored filters have been extensively used in architecture in the form of glazing - from Islamic glass decoration in mosques, over architecture classics such as the Ronchamp, to the work of contemporary architects and artists such as Steven Holl and Olafur Eliasson. The use of colored glazing in buildings has the ability to change the atmosphere and the perception of colors in the interior. This has always held an important role in religious architecture and in contemporary cultural buildings, museums and art exhibitions.

Similarly, RGB visualizations present a great potential for the representation of architecture and urban design, as the encoded layers of information can reveal the internal structure of a building or cast light on different components of an urban plan such as built volumes, green spaces, circulation, pedestrian flows and infrastructure.

The benefits of RGB visualizations lie in the fact that certain aspects or features can be isolated and presented, providing insight into the anatomy of a building or a product. They can form an alternative to exploded axonometric views or other infographics, enabling clients, audience or students to obtain an enhanced understanding of a project, by hiding or revealing information on demand. RGB visualization may be used as a tool to present or instruct, creating an interactive experience of space and information.

Elements that can be represented in RGB images include human and traffic flows, urban maps, vertical communication in high-rise buildings, classification of spaces such as private and public, facade constructions, structural elements such as space frames, slabs and cores, as well as forces within structures (topological optimization).

ANALOGUE AND DIGITAL VISUAL FILTERS - A POST-DIGITAL APPROACH

In 1995 Feiner et al. introduced the use of emerging technologies of augmented reality to "illustrate, understand, and modify architectural anatomy" (Feiner et al. 1995). The aim was "to explore relationships between perceived architectural space and the structural systems that support it, to help understand architecture in ways that are impossible to achieve by simply viewing the perceptual reality of completed spaces" (Feiner et al. 1995).

The methodology for RGB visualizations presented in this paper aims to employ a combination of digital and analogue techniques, re-visiting old tools and utilizing them in a new context. This is in accordance with Mark Burry's suggestion with regards to digital media, that "before we abandon old tools for new, this is a good moment to put the brakes on. Hybrid activity demonstrates unequivocal benefits to the design process" (Burry 2005).

In line with the post-digital tendency to re-visit traditional tools, this research suggests a novel use of decoder glasses for architectural visualization, with the aim to engage the viewer, and to enable her/him to selectively view certain aspects of a building in an interactive and playful context. It represents an attempt for disenchantment with purely digital tools and a revival of "old" media, understanding terms like "post-digital" or "retro-analog" as a hybrid of "old" and "new" media (Cramer 2015).

While the term "post-digital" discusses the "contemporary revival of analogue technologies" (Thoren et al. 2017), it also questions the "presupposition of binary divisions between the dichotomies 'users'-'non-users' and 'analogue'-'digital'" (Thoren et al. 2017).

As Fure points out, the "post-digital" is not "beyond," "anti-," or simply "not" digital (2018). Instead, it is "focused less on novelty and more on the hidden aspects of computation. Post-digital design discourse calls for a critical examination of the tools and technologies we take for granted (Fure, 2018).

COMBINING ANALOGUE AND DIGITAL TOOLS FOR ARCHITECTURAL VISUALIZATION

The digital era initiated a big shift in architectural visualization. In this regard, the use of "layers" in digital imaging, drawing and modeling (such as in Photoshop, Illustrator, AutoCAD, Rhinoceros 3D) played an important role. Layers are useful to create flexible and editable images, and to keep track of the hierarchical structure of design information when dealing with complex projects.

In the pre-digital era, overlays were produced using tracing paper, transparent paper or collage techniques. The introduction of digital tools allowed architects to employ layering techniques in new ways. The current generation of architects became familiar with the concept of organizing projects in layers, and with handling their complexity by turning layers on and off. However, when aiming to transmit certain aspects of a project to non-architects, students, or clients who are not familiar with a particular project, or a digital tool, it is not always feasible to reveal different layers of visualization without the use of a compatible software. Particularly for those who are not experienced with the organization of visual information in layers, the use of color lenses can provide an alternative and quite playful way to hide or reveal layers of architectural information.

There are several ways to visualize hidden information of buildings or to offer an insight into construction sequences and assemblies. Among the most common ones are exploded axonometrics, superimpositions and IKEA-style assembly models.

Architects such as Eisenman and Tschumi used exploded axonometric drawings, separating different elements or levels to make complex designs understandable (Figure 1). For example, Tschumi developed the project of the Parc de la Villette by the superimposition of three layers - points, lines and surfaces (Figure 2).

The above-mentioned visualization techniques are still in use today to produce informative and understandable drawings of complex buildings. For example, Coop Himmelb(l)au uses exploded axonometrics or perspectives to show construction systems or programmatic elements in the project BMW-world. Nowadays, such visualizations can be created quite easily from digital drawings or 3d-models.

Alternatively, complex information can be visualized with the proposed RGB technique. This technique exploits the benefits of digital layers in combination with analog filtering tools to create isolated views of complex buildings. It compiles a multitude of visible layers of a project to create a merged layer. The RGB visualization method is a useful tool to see the overlay of elements, while also being able to highlight different layers using the color lenses.

With the broad use of digital media in architecture, contemporary buildings have overcome the limitations of standardization, and nowadays there are buildings with unique morphology and extravagant geometry. However, for the majority of the buildings, only the external shell is visible from the outside, and information on their anatomy can only be found in specialized literature. The project "anatomy of a building" aims to reveal the hidden information about how a building functions, how it is constructed, how it looks from the inside, or how it looked during construction phase. Having studied a great variety of buildings with such features that are worth to be shared with a broader public, the authors have undertaken a series of case studies to highlight or isolate certain pre-selected building components. The RGB images generated for this project offer an opportunity for interactive exploration of visual data, presenting an alternative way to interact with technology.

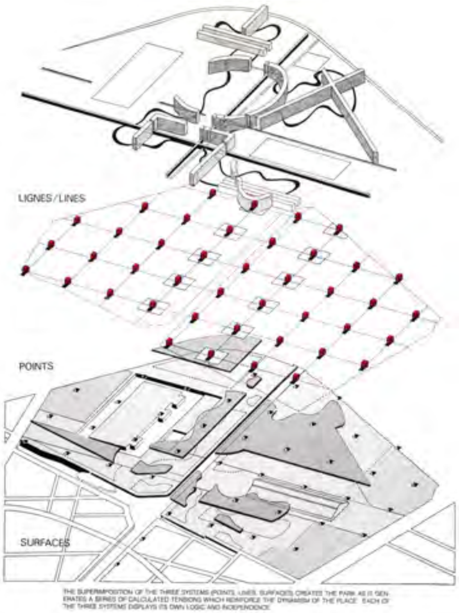


Figure 1
Exploded axonometric of Parc de la Villette by Bernhard Tschumi (Tschumi 1988)

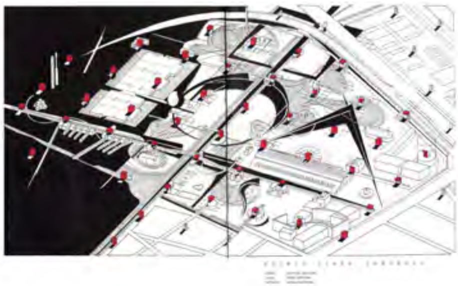


Figure 2
Superimposition of Parc de la Villette by Bernhard Tschumi (Tschumi 1988)

HOW TO BUILD AN ARCHITECTURAL RGB VISUALIZATION

This section explains the methodology used for the creation of a superimposed RGB visualization from an existing 3D model, image or photograph. The workflow includes steps in Rhinoceros 3D and Photoshop, to create the images and to test them through color filters.

Based on the color theory and on what the human eye perceives as color, the three primary colors of light in "additive color mixing", red, green and blue (known in computer industry as RGB) when mixed with each other form cyan, magenta and yellow (also known as CMY) - red+green=yellow, green+blue=cyan, blue+red=magenta (Figure 3).

In an illustration that comprises of CMYK colors, the colored lenses act as filters, absorbing all colors of light except the actual color of the lens. Therefore, decoder glasses that are red absorb blue and green light but allow red light to pass through. It is like removing certain colors of light. This principle is also known as "subtractive color mixing". In this mixing model, cyan, yellow and magenta are considered the primary colors. Therefore, a color lens subtracts all the wavelengths NOT in the color filter. In the Primary Color Wheel for light, the blue and yellow colors are placed diametrically opposite. By applying a yellow filter to magenta, this is canceling out the blue and making it appear as red.

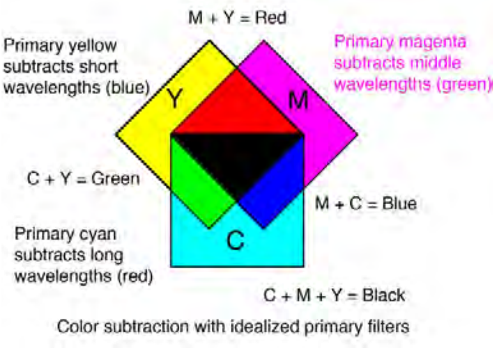


Figure 3
Subtractive color mixing (image source: http://hyperphysics.phy-astr.gsu.edu/; HyperPhysics © C.R. Nave, 2017)

Following the model of "subtractive color mixing", the RGB visualizations developed in this research consist of superimposed layers in CMY colors, leading to a change in the color perception when viewed through RGB lenses. The red lens (or light) filters out magenta and yellow, and highlights the cyan layer. The green lens (or light) filters out cyan and yellow, and highlights the magenta part. The blue lens (or light) filters out cyan and magenta, and highlights the yellow layer. When filtered by blue, the highlighted color (yellow) appears as black, while the white background appears in the color of the lens (blue).

The generated RGB visualizations work in conjunction with the multidimensionality of a surface, with which people can interact. They can be perceived as multicolored graphics in overlaid condition or untangled when viewed through colored filters.

A SERIES OF CASE STUDIES

In order to test the aforementioned strategy for creating RGB visualizations, the authors have developed a series of case studies, mainly based on plans, 3D models and photographs of well-known buildings and urban design projects. The projects selected are iconic buildings that due to their unique geometry, function or construction logic are worthy of our attention and analysis, and most importantly have a great wealth of secrets to reveal.

The selected buildings are:

Fondation Louis Vuitton by Gehry Partners. Gehry is a pioneer in creating buildings with complex geometries, such as the Guggenheim museum in Bilbao. The Fondation Louis Vuitton (2014) is a Cultural Center in Paris, France with a facetted free-form geometry [4]. It consists of glass sails carried by a complex steel structure, surrounding the internal cores and functions. The RGB visualization of this project allows the viewer to see not only the external skin of the building, but also the steel structure (cyan), and the internal cores and programmatic volumes (yellow, Figure 4).

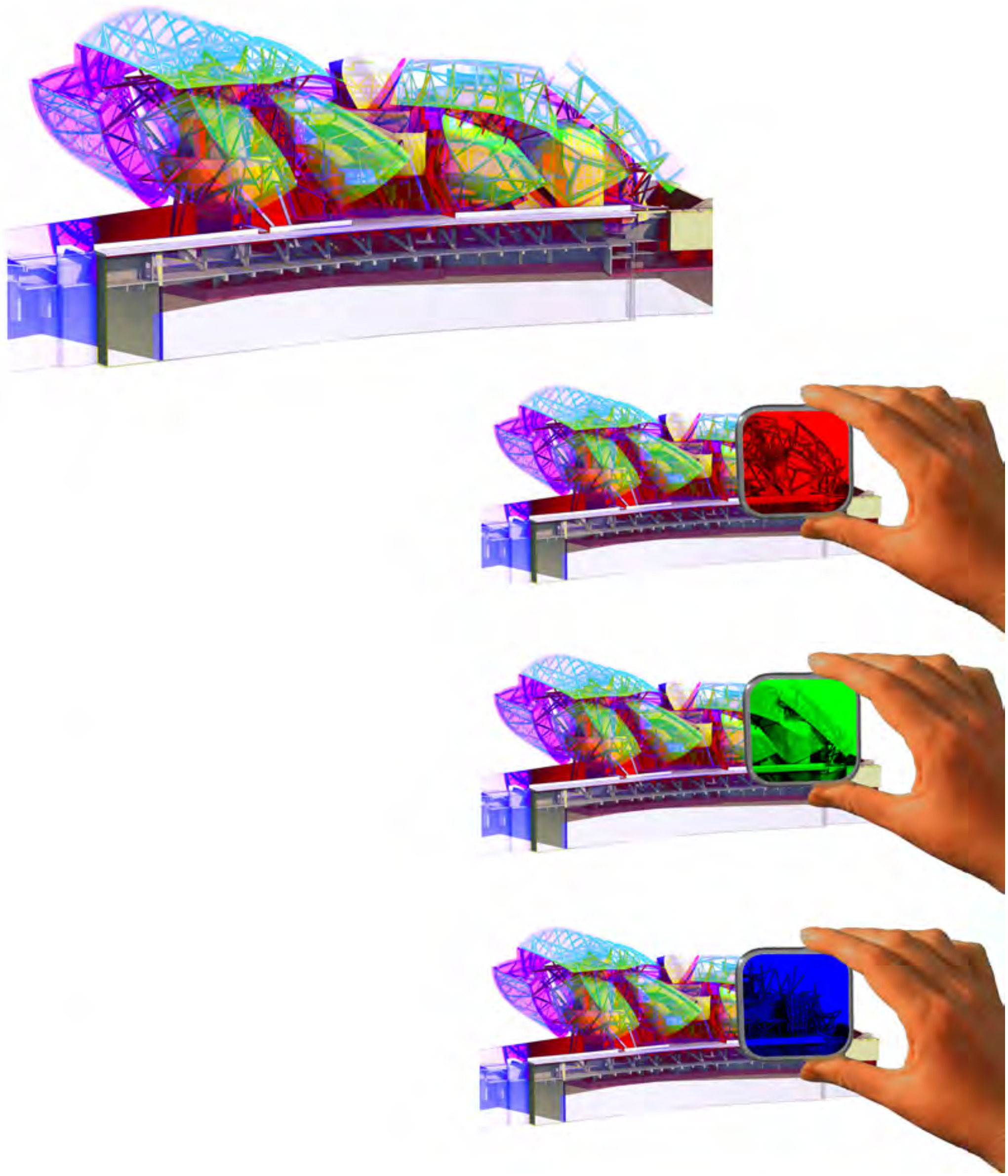
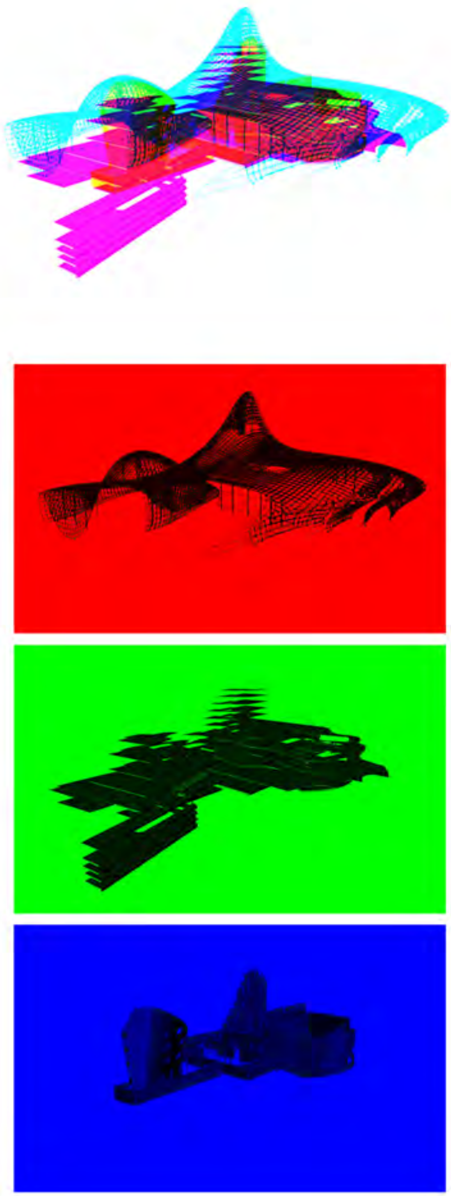


Figure 4
RGB visualization of the Fondation Luis Vuitton building by Gehry Partners. The red filter reveals the structure of the building, the green filter shows the external building skin, and the blue filter reveals the internal core of the building.

Figure 5
RGB visualization and filtered views of the Heydar Aliyev Center by Zaha Hadid Architects. The red filter reveals the structure of the building, the green filter shows the slabs, and the the blue filter reveals the internal core of the building.



Heydar Aliyev Center by Zaha Hadid Architects. Zaha Hadid is known for free-form architecture with sleek continuous surfaces, but the structure behind it is mostly hidden. The Heydar Aliyev Center in Baku, Azerbaijan (2013) is a cultural center with a fluid geometry comprising of multiple waves, emerging out of the ground. While visitors can only see the impressive homogenous facade, the presented RGB visualization gives an insight into the structural system behind the skin, consisting of a steel framework combined with a concrete structure of cores and slabs [5] (Figure 5).

CCTV-Headquarters by OMA. The CCTV-Headquarters, an iconic OMA in Beijing, China (2012) for the China Central Television (CCTV), represents an alternative to the typology of the skyscraper, consisting of a 3-dimensional loop with a 75-metre cantilever [1]. To realize this geometry, a cantilevering steel-structure behind the building's skin was developed, which carries the whole building. One layer of the RBG visualization highlights that structure, whereas the other two layers show the internal core respectively the vertical communication and uses (Figure 6).

Seattle Central Library by OMA + LMN. The Central Library in Seattle, WA, United States (2004) represents a new type of library, "organized vertically against the traditional horizontal organization of traditional libraries" (Barba 2018). It consists of vertically stacked volumes and platforms, which are shifted against each other and define the geometry of the enclosing polygonal skin. The RGB visualization shows the external building skin, the interior space's relation between open and closed, as well as the structural components (Figure 7).

Beijing Olympic Stadium by Herzog & de Meuron. The "Bird's Nest" in Beijing, China (2008) is an iconic building, known for its visible structural network. The multi-layered lattice encases the building, but also facilitates an in-between space between interior and exterior. The structure consists of primary trusses, carrying the roof and the facade, braced by secondary elements (Brown 2009). The RGB visualization reveals the well-organized primary structure system underlying the seemingly chaotic lattice (Figure 8).

BMW-World by Coop Himmelb(l)au. The BMW-World in Munich (2007), an event and delivery-center for BMW, is an iconic building, dominated by a double-curved, sculptural roof, hovering above a large open hall [8]. The roof, anchored by the double-cone, is constructed by a complex steel framework. The programmatic elements are located within the volume of the roof, as well as under it. By means of the RGB visualization technique, the roof panelization and the solar panels are shown, as well as the complex steel framework and the programmatic building volumes in and under the roof.

Centre Georges-Pompidou by Renzo Piano and Richard Rogers. The Centre Georges-Pompidou in Paris (1977) is included in the list of case studies for historical reasons, as an archetype of the 20th century that pioneered the use of actual colors to indicate different elements of circulation, such as air, electricity, water, escalators and lifts [6]. The RGB visualization highlights three components of the building, namely the structural system, the circulation of people and the ventilation concept.

London City Hall by Foster + Partners. The London City Hall (2002) is a glass building in the shape of a geometrically modified sphere [7]. The RGB visualization of this project takes a completely different approach than the previous ones. Here, the layers reveal, on the one hand, two construction stages, and on the other hand, the energy concept behind the form, explaining in a schematic way the relationship between the building's shape and its environmental performance.

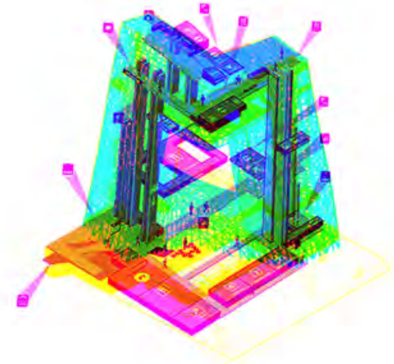


Figure 6
RGB visualization of the CCTV-Headquarters by OMA, showing an overlay of the structure of the building, the internal core , and the vertical communication and uses

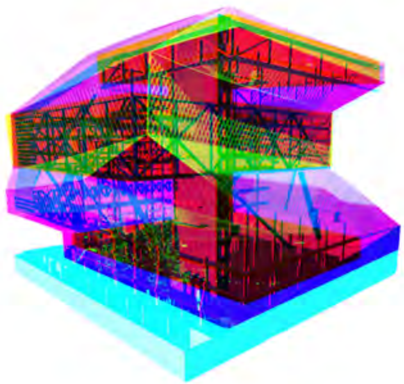


Figure 7
RGB visualization of the Seattle Central Library by OMA + LMN, showing an overlay of the structure of the building, the internal core , and the external building skin

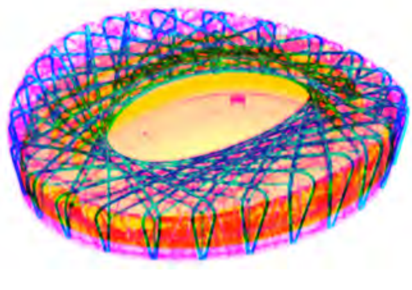


Figure 8
RGB visualization of the Beijing Olympic Stadium by Herzog & de Meuron, showing an overlay of the primary structure system, the secondary structural elements and the internal core

CONCLUSION

The project “anatomy of a building” introduces an analogue post-digital concept for educational, representational or artistic purposes. It investigates a new take on architecture visualization, appropriating concepts from other fields for architectural purposes. In this study, an interactive, playful approach is taken by using physical color lenses to highlight certain aspects of digitally-prepared multicolored images.

Color mapping is not new in architectural representation, as it can be used complementary to line, structure, form and detail, extending the visual vocabulary (Minah 2008). However, the visualization strategy presented in this study provides viewers with the new ability to select what they see in a drawing without the need of a computer to switch layers on and off.

In line with the post-digital tendency of revisiting old tools, this research merges digital and analogue media. Digital tools and well-known concepts such as layers are employed, but they are utilized in a new way, to actually formulate the compositional elements of an image. They are overlaid with the pre-digital physical-based interface of color lenses.

As it can be seen in the images presented in the case studies, the buildings are visualized in an unconventional way. In these superimpositions, new color patterns can be seen in the intricacy of the overlaid lines and fields. The images display an idiosyncratic aesthetic that draws the viewers’ attention and curiosity. On the one hand, they visually represent the complexity of the selected projects, on the other hand, they allow for isolated views.

Future work aims to expand the current research to moving image and to create videos or interactive animations, where the user can alter color filters to visualize different information.

The authors will present a live demonstration of their case studies during eCAADe + SIGraDi 2019 Conference in Porto. The audience will be provided with colored lenses so that they can test the RGB visualizations and delve into the anatomy of buildings, objects and urban plans.

IMAGE SOURCES

The RGB visualizations presented in this paper are compilations based on other images found on online platforms such as Pinterest, Google images, as well as books, magazines and social media. Some of the main sources of visual material are:

http: / /www.architectureweek.com /2006 /0111 /images_ /12913_image_2.jpg

https: / /es.wikiarquitectura.com /edificio /sede-de-la-cctv /

http: / /www.rasmusbronnum.dk /2009 /02 /21 /engineering-koolhaas-arup /

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Prototyping shifts in design scale

The "Carotid thermo-regulator" as intelligent body architecture

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This paper explores the use of smart technologies like physical computing with a sensor and an actuator, to create a prototype of a wearable technology, which augments our interaction with the environment, and people. The initial design idea was based on an empirical study of varying body heat signature patterns corresponding to emotions. However, we are interested to expand the discussion beyond technical issues in the design process, to reflect on the broader relationship of the human body with space and people. The study raises some important questions vis-à-vis current mobility and scalar reduction of Technology today: What is the relationship between architecture and the human body? Can a wearable technology be used to indicate, and express a fluctuating emotion? How would a traditional garment element evolve to respond to a new requirement or program? What are the appropriate scales we should refer in order to design our surrounding space? What sort of expertise is required to shift in design scales?

Keywords: *Performance, Rapid prototyping, Physical computing, Micro-controllers, Human body, Scale*

This study is a sequel to the Reshape15 Competition, an international wearable technology design competition. The authors constitute the third prize winning team, featuring a design for a "Carotid Thermo-regulator". The Competition considers fashion as a fertile ground for exploring physical computing and digital fabrication ideas addressing the following statements. "Data becomes beauty, interaction becomes emotion. As a result, a new aesthetic is emerging" (Reshape | R15 - Reshape, 2015). The project benefits from funding from the National Council of Architectural Registration Boards (NCARB). The funding supported a new course aiming at integrating the practice and academic inquiry. The course is titled "Performative Parametric Design", and employs the physical computing and parametric modeling as tools to address building performance.

The design team starts the investigation by looking at the fashion history across different cultures. During the research process, the team became fascinated by different fashion trends; for example, ones that were developed to alter anatomy to fit local beliefs and aesthetic preferences. Some examples include the Egyptian head binding, Chinese foot binding, and Red Karen neck extension. The latter involves the use of brass tubing to form stacking rings pushing the jawbone up, and the collarbone down by coiling the tubing to add more rings. The team decided to focus on the design of a neckpiece.

The human cervical region has been celebrated by historical and contemporary fashion trends alike. Either through concealment or elaborate exposure, tailored garments and accessories like the "Ruff' have been used since the 16th century to prevent the shirt from being soiled. While some versions of the former denoted an aristocratic provenance, the latter has been associated with radicals, academics, philosophers, intellectuals and politicians. The design of ruff has changed over time, and become a shirt collar. The team would like to transform the more familiar neckpiece by giving it a new function to investigate how a traditional typology can be transformed. A previous study on temperature map as a result of emotion piques our interest (Nummenmaa, 2013). However, it requires an extensive network of sensors in order to detect the pattern. A temperature change may indicate a mood shift.

This project re-imagines this area of the body through a prosthesis, which extends aesthetic preoccupation to consider the regulation of thermal comfort (Fanger, 1970). Our premise stems from the traditional Ruff which evolved from a small neck piece to high ruff or collars during the Elizabethan era. Historically, ruffs have shrunk or enlarged transforming into cuff and skirt through evolutions, incorporating wooden support in some iterations (Hughes, 2011).

PROTOTYPE DESIGN & PERFORMANCE

Our proposed carotid prosthesis embraces physical computing and anatomical expression to create a dialogue between technology and nature. The design considers a garment as a vessel for the human thermal adaptation. Interestingly, body temperature amplitude and patterns correlate to standard biophysical incidences like the heart and respiratory rate as well as emotion (Nummenmaa, 2013; Davies, 2009). The garment includes a microprocessor, sensor, pump, wearable enclosure, closure, fasteners, and heat exchangers (Figure 1). A pulse sensor is placed over a carotid artery area to detect a temperature change in a non-invasive manner (Childs, 1999; Buller, 2013; Imani, 2016; Jay, 2013). Its reading from the Carotid artery controls a peristaltic pump transferring the body heat to the heat exchangers/sinks similar to a fluid cooling system for an electronic component such as a computer CPU. The pump circulates a fluid medium in a closed loop tubing system passing through inline heat exchangers that dissipate the collected heat through the natural convection.

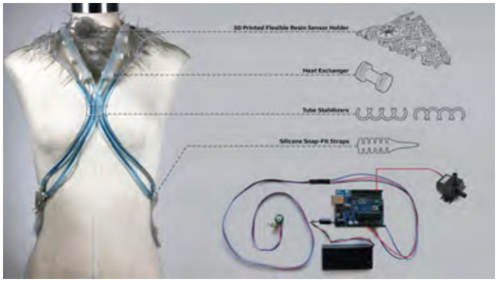

Figure 1
A diagram showing component assembly of the design. A pulse sensor connected to an Arduino controlls liquid flow through a pump.

Integrating these components within a wearable item, the team carefully considers minimum weight and non-disruptive user presence. Soft sheet materials like silicone rubber and flexible resin are employed. The silicone sheet can be laser-cut to form the back closures, fasteners/ties and the enclosure; while other custom elements are 3d-printed using the flexible resin to achieve geometrical complexity. The silicone sheet serves as a primary (inner) layer for attaching a 'soft' 3d-printed layer, which in turn secures the liquid-tubes (Figure 2). To ensure skin breathability, a pattern of holes is cut from the silicone surface using a parametric definition, which translates color data from thermal IR imaging of users' cervical area into a gradient pattern (Figure 3).

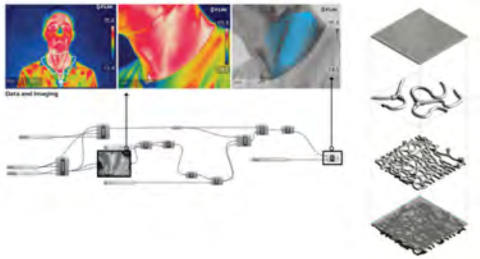

Figure 2
An Infrared thermography of the wearer's cervical region (One of the authors is used as reference for pattern generation).

Figure 3
A laser-cut silicone sheet for the flexible piece framing the neck.

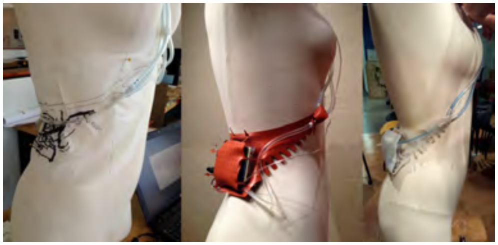

Figure 4
Design Process: Early sketching using proportions of the human body; early prototype with silicone rubber; final prototype.

Figure 5
Testing of 3D-printed pump; Design Iterations for liquid flow control: 3D-printed pump (1), off the shelf pump (2) and peristaltic pump (3) used in the final prototype.

The effect resulting from the transformation of thermal data into graphic becomes an inherent ornamental quality of the piece. It provides a clear reference to the internal blood vessel network of the neck; this component secures the heart rate sensor and tubing and is attached on the silicone piece via a number of fasteners, feather-like barb ties that act like buttons or toggles. The designs of the barb ties and the back closures are inspired by barb ties used to hold thermos-formed plexiglass pieces in an installation led by Phillip Beesley as a part of the class activity (Phillip Beesley Architects, Inc., 2015). The back closures mark the top of the spinal column, cervical vertebrae. Its repetitive arrangement is similar to the cervical vertebrae to further reinforce the idea of reflecting the anatomy onto the garment. In addition, ties are also used as ornamental elements to create a silhouette similar to a fur collar used to provide warmth in winter.

The original plan includes the integration of the pump into the 3d-printed layer in order to remove attention from that area to the higher part of the neck where the sensor is located. However, the size of the pump that we have is too large. For the prototype, the pump is located in a pouch made of a laser-cut silicone sheet, and located in the lower back region (Figure 4). The shape and arrangement of tubes follows the diagram of blood vessels and hot spots in infrared reading in order to effectively transfer body heat. The prosthesis serves as a fashion statement, celebrating the importance of the cervical area as a liaison between the central body organ (heart) and the body's processing unit (brain).

A centrifugal pump is the vehicle for moving the liquid medium through the network of tubes (Figures 6, 7). This device was designed to move the cooling heat exchange liquid by transferring rotational energy from one or more driven rotors. Fluid enters the rapidly rotating chamber along its axis through an inlet and is propelled by centrifugal forces through the outlet. The use of a stereolithographic (SLA) resin 3d printer was advantageous for achieving specific design outcomes: to be symmetrical and centrifugal in the interior chamber in order to direct water flow accurately, ergonomic on the exterior to create a homogenous connection with the pouch, and finally for it to be water-tight. The two-part pump (Figure 5) was created using SLA Form Labs printer and then assembled together manually. The lower part of the pump included the centrifugal container which holds the liquid in a chamber and also has an inlet and outlet. The upper part, or cap, houses the rotors which were cut and formed from thin ply sheet metal. This version included two rotors that direct the flow towards the outlet. One major design challenge with using a traditional pump was creating a water-tight system. Problems were posed during prototyping in which the laser-curing of the 3d-printed parts created moments of porosity and the upper and lower parts were not sealed together properly. As a result, prototyping the pump was abandoned in view of a tight time-frame when the project was taking place (2015) and instead, a readily peristaltic pump was integrated in the assembly (Figure 6).

BUILDING AND BODY : CRITERIA ACROSS SCALES

The correlation between Clothing and Architecture has been noted by several architects in the past, including Adolf Loos (Gesetz der Bekleidung: Law of Dressing), and is presently revived through research that utilizes the latest technology in digital fabrication, integrating "smart" layers within daily garments. The consideration of "smart clothing" which is connected online and allows the adjustment of parameters through portable technologies like smart phones is promising because it can be situated within a broader framework of energy conservation: perhaps it is more efficient to control the micro-climate around our body, instead of the temperature of an entire building. The design of responsive wearables should not be seen necessarily independently from the architecture around them, even if these could indeed function autonomously. There is some merit in contemplating the performance of a system across scales. As architecture becomes increasingly interactive, it may reconcile the performance of the building with that of its users through smart prostheses within clothing (built-in sensors, kinetic components) that control building accessories (eg. parts of a building's façade) or, reciprocally, are controlled by the building's behavior in reference to a particular criterion. For example, if the external temperature on a building shell - recorded by built-in sensors on the façade - exceeds a certain level, a switch for operating the pump on the interactive collar could be activated, thereby reducing temperature locally (neck area) to offer relief from the heat. This may be a significant step towards reducing energy consumption for cooling buildings in warm climates, as the micro-climate induced by the clothing could compensate for a portion of the temperature shift necessary to reach the desired range of thermal comfort: in order to maintain a benchmark temperature for optimum comfort within an office building - i.e. 23-26 degrees Celsius (73.4F- 78.8F) in the summer- one may use A/C to get closer to the desired temperature, then regulate the temperature around the body to reach the final value, achieving substantial energy economy.

In this sense, we may consider the building and the human body as two separate parts of the same (digital) circuit which are connected with each other. According to the late Bill Mitchell, Professor of MIT's Media Lab, this circuit - which is in fact, the internet- acts as a receiver of signals from the human body, which are then translated through clothing: "Clothes have traditionally shaped our first interface with the physical world as much as our personal electronic devices or intelligent clothes are now creating interfaces between our nervous system and the worldwide digital net." (Mitchell, 1996). Objects at a wearable scale, may therefore belong to a larger wireless network which includes building systems at large.

In the context of "design thinking" architects have a lot to learn from this reciprocal scalar transition; an exhibition on design and science (Design and the Elastic Mind, MoMA 2008) addressed this overlapping of scales. According to the exhibition (and MoMA's Architecture and design) curator Paola

Figure 6
Final prototype for Carotid Thermo-regulator, using custom-made 3D-printed and laser-cut components: overall assembly; photocell used to test the wearable liquid circuit, replacing the heart sensor as a trigger currently (The pulse register will be integrated in a revised version); Pump; power source; Arduino micro- controller.

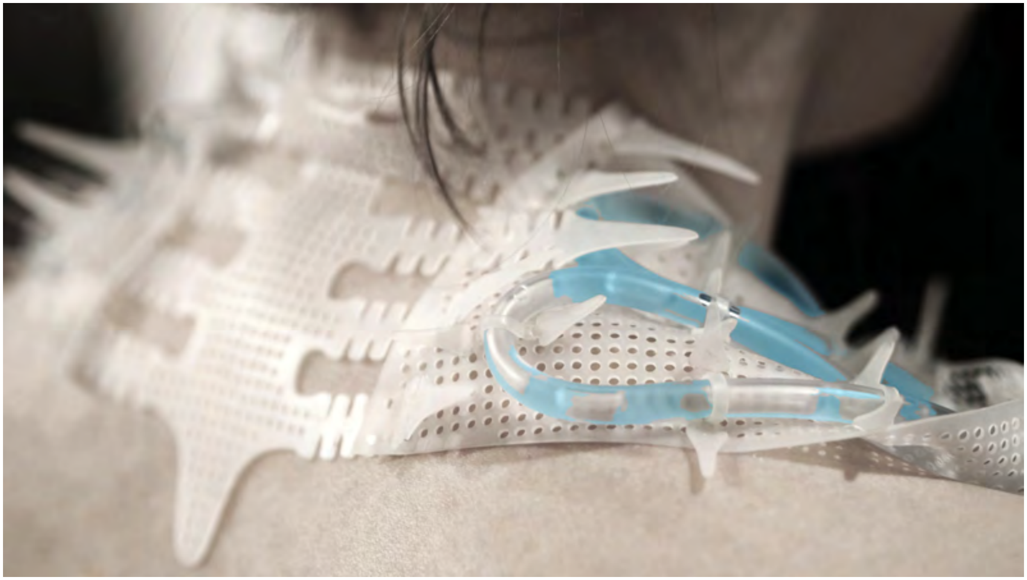

Figure 7
Liquid medium flowing through tube network to transfer heat from the neck region to heat exchanger.

Antonelli "...what we discovered was that scale was no longer a matter of size, but rather a matter of complexity...It doesn't make sense any more to distinguish design disciplines because of the materials they use, the dimensional scale they tackle, or other old-school kinds of criteria." (Antonelli 2017) While this cross-scalar connection exists, it is critical for architects to understand how to extrapolate principles from one scale to another; in his essay "Size Matters", Neil Leach reminds us of the 1977 film "Powers of Ten" by Charles and Ray Eames (Leach 2017), which illustrates aspects of life ranging from the entire universe to a single quark. Today's digital tools for drafting, he observes, have no scale except at the moment of printing (or prototyping). We should, therefore, be cautious to not dismiss the differentiation of material performance at different scales, as scaling an element in 3 dimensions exponentially changes the volume, which means that material behavior changes radically. Leach gives an example of both organic matter (bone) and man-processed material (steel); proportionally scaling the material skeleton of a high-rise building (i.e.Empire State) would not suffice, we would need to reconfigure its structural logic as scale increases (see Flotsam & Jetsam, SHoP Architects, 2016).

COLLABORATION STRUCTURES AMONG DESIGNERS: CRITERIA ACROSS DISCIPLINES

The aesthetics which are formulated through the incorporation of technological accessories in wearable solutions is for the moment loosely defined, due to its infancy. Nevertheless, an ongoing discussion is already taking place among architects and other artists and fashion designers. Early discussions on this topic were instituted during a symposium organized by architect, professor and theorist Neil Leach, and titled "Body Architectures" (2016). Fashion designers like Iris Van Herpen and Mary Katrantzou are introducing rapid prototyping technologies and smart accessories to produce unique garments which consider performance beyond clothing's rudimentary function or artistic appeal, to address some Performative aspect of their design. In doing so, they often reach out to architects like Behnaz Farahi, Nicolo Casas, Neri Oxman and Philip Beesley.

Beyond our daily practice of technology and its performance, it is important to situate this design work within a discussion on Architectural theory and responsiveness in architectural education. The work presented in the aforementioned symposium ("Body Architectures") delineate our intention as architect for an explicit shift of Scale in our work especially in dialogue with other fields like fashion design and art. Can the future projection of this tendency forecast an impending augmentation of the required skills in architecture graduates? Will this challenge the traditional architectural pedagogy towards greater collaboration with external consultants like engineers and programmers within the curriculum? It is worth considering the notion of "design agency" as such design protocols become more popular, because the concept of intellectual property assumes a broader, more collective character.

In this collaboration among designers of various crafts, the visual dimension of Architectural output should not be overlooked. According to Paola Antonelli, the formal expression can serve as a tool of communication: "I have always insisted on the fact that physical elegance...is a form of communication...in nature the first means of communication is form...if you were able to take a complex scientific concept and manifest it so that its gorgeous appearance cuts across resistance and disbelief, then you're going to have a better chance...to reach a wider audience" (Antonelli 2017). Notwithstanding the performative requirements of the Carotid Thermoregulator prototype, its aesthetic expression is fundamental as this is situated within the context of fashion, and - referring back to Antonelli- may depend on the visual capacity of form to communicate the complexity of the systems involved through an embedded visual (formal) elegance. It is interesting to note that the design of the prototype transformed considerably as the design process revealed constraints related to the physical computing aspects and also the circulation of the fluid.

CONCLUSION

The human body can be identified as the inherent network of interior and exterior organs protected by our outer layer, the skin. Throughout the years we have created tools or garments that enhance our interaction with the environment (eg. shoes to protect from uncomfortable surfaces, sweaters to mimic the use of fur, and more recently, the smart phone to amplify our computing power and memory which is arguably attached to us as often as these garments). Does this make us unofficially cyborgian by default? As discussed earlier, the notion of the "extended body" has preoccupied several designers and theorists in the past, and current scaled digital technologies have facilitated the integration of smart devices within a wearable context. We are interested to discuss the potential of approaching a design problem from a perspective of product design, interactive performance and aesthetics, assessing their reciprocal dynamics in the process, as well as a resulting visual language which echoes the current constraints of material and portable technologies.

If the human body is a network of systems working together internally, and our tools and garments are only individual enhancements, how can we shift the focus to allow for a unified network of systems which are integrative to create a smarter, yet more playful, humanitarian experience? There is, naturally, a margin for optimizing this as a "product". It should be mentioned that the "Carotid Thermoregulator" was designed and prototyped before the dissemination of work of similar context, like the projects featured in the "AD: 3D-Printed Body Architecture" issue (2017) - even if some of that work was in progress at the same time (2015). Unlike these projects, this work is not entirely dependent on 3D printing; in fact, it is possible to fabricate without a 3D printer. Considering the advancements in 3D printing, there are potential benefits from integrating this technology to evolve the next generation of the prototype into a more compact product which can be seamlessly integrated into our range of existing fashion accessories. In order to better address the objective of the wearable, which is to circulate liquid effectively and provide visual integration as well as thermal insulation, perhaps research on material customization/-combination within one prototype should be examined (see the work of both Neri Oxman and Behnaz Farahi). During this investigation, one should keep in mind the idiosyncrasies involved in material performance when transitioning scales (Leach 2017).

On a broader level of architectural discourse, this work promotes design thinking and criticism with regards to the role of the architect and our "Agency" in the act of design; during the mid-2000s, the emergence of digital fabrication promised, according to some practicing architects and researchers (i.e.Kieran Timberlake) the repositioning of architects in the center of the construction process, giving us more control. This broadening and strengthening of the architect's position sort of echoed the lost Brunelleschian model of the "master-builder", which had disappeared effectively since the split between design and construction was initiated by Alberti in the Renaissance. Interestingly, Neil Leach suggests that the same Digital Fabrication technologies are today promising for almost the contrary - they allow graduates with architectural training to be absorbed by similar but other industries like fashion design, food, jewelry, etc. and find a home thanks to the skillset inherent in our training. This points to a return to the spirit of the Bauhaus, which according to MOMA's Paola Antonelli, is necessary vis-a-vis the blurring of scales across design fields: "Everybody who studied at the Bauhaus went through a primary curriculum that was very much about learning the rudiments of all the arts, and then branching out. That kind of initial core is, in my opinion, still extremely important...if you have a strong engineering, historical and theoretical background then you can move in any direction you want." In a technologically-driven society where specialization is on the rise, it is interesting to consider revisiting architectural education towards a more generalist approach which can render Architecture graduates even more robust, ready to face a design industry where scales, tools and skills overlap.

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Color Harmony Integration-driven Design Process for Aesthetic Village

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This paper describes the color design process of the house in the village. The color design process proposed in this paper constitutes design stages such as color selection, color application, and color design analysis and evaluation. In the color selection step, a method of arranging colors using a color pallet or a color scheme is described. The color application stage includes the process of creating a village color design alternatives by specifying the color information of the hue, value, and saturation based on the BIM model. The color analysis stage is to numerically identify the color design attributes of the generated color design alternatives. The reason for color analysis and evaluation is to produce various design alternatives with the color harmony and improve the quality of the design.

Keywords: *Color Palette, Environmental Color, Color Harmony, Color Scheme, Color Design Analysis*

- **INTRODUCTION**

It is important to design a beautiful village to improve the quality of life. However, most of the villages built in modern times are not very beautiful, nor are they characteristic designs, nor do they reflect regional characteristics. If we solve this problem and create a more beautiful village than now, can we make people happier? So how do you make a beautiful village? There are many ways we can think of how to make a beautiful village. One of the ways to create a beautiful village efficiently is to utilize colors(Boeri 2017, Gou and Wang 2008, Lancaster 1996). Until now, color is a design element that the architect did not show much interest in comparison with other architectural elements in order to improve the quality of the design. Why, then, did architects have less interest in color?

This is because the form is considered more important than the color in order to meet the required function. Another reason is that architects have received relatively more education in terms of form, but perhaps less educated about color. Or it may be because color was accepted as not a design area of architecture. However, considering the times when emotion is important, color is just as important as form. Generally, colors are considered emotional and forms are considered rational. In this regard, this paper is motivated to deal with the process of color design, which architects have not dealt with design process heavily. And to provide aesthetic and well-being experiences for people by improving the aesthetic characteristics of the village. This study aims to improve the aesthetic characteristics of villages by developing a color harmony integration-oriented color design process that architects can easily apply in collective housing deign.

In general, in traditional color design, it is true that color design has been carried out by designer intuition rather than other designs. This is because color has the property of design that is highly subjective and connected with emotion. The color harmony problem, which has also relied on the intuition of the designer, is one of the most important issues related to color design. In traditional color design, the quality of the design has been affected by the ability of the intuition and subjectivity of the designer. Another problem with traditional color design is that some design alternatives are created and then the final design is decided. However, this problem can be solved by using digital color. In other words, it is possible to systematically design color by the design process based on digital color. Previous research on color design process has been insufficient. In particular, there have been few studies on architectural color design process using digital technology.

The quality of color design can be improved by utilizing the color design process. It will not only provide people with the pleasure of aesthetic experience, but also enhance the identity of architecture. In this sense, this study deals with the problem of color design process. This study attempts to deal with the color design process in terms of the color design of a village with aesthetic experience. The color design process described in this paper focuses on the integration of colors. The integration of colors has much to do with the harmonization of colors such as the unity of colors.

- **Color Design Process Aiming Color Unity Towards Harmony of Consistency**

Color is one the most important yet difficult factors in visual design. One challenge is generating harmonious color schemes(Hu et all 2012). Color in the man-made environment influences spatial perception by affecting the character of the space, the clarity or distortion of the spatial envelope, its proportioning, and its articulation(Tosca 2002). Color is an element of architecture, thus color design have to be integral part of architectural design process. From this point of view, the color design process determines the direction of color design and greatly affects the quality of color design. Despite this importance, however, it is difficult to find a color design process that architects can easily use. This paper, which was started with the focus on this problem, has the motivation to develop a color design process that architects can easily and systematically use. The color design process(Ju and Lee 2018, Smith 2003)) to be discussed in this paper consists of three stages shown in Figure 1.

Step 1. COLOR SELECTION

The first step is the selection of the color scheme to choose the appropriate color in the stored color scheme database. The choice of color scheme is found by the search term of emotional words from regional images. In this paper, color palette FX is used to create color scheme through regional images of villages are located [1]. The FX analyzes color images and provides harmonious color scheme with colors with the form of Hex, RGB, and HSL. After that, color palette can be created according to color schemes. The color scheme is generated considering the harmony theory of color(Birren 1969, Hard and Sivik 2001, Hu et al 2014, Kopacz 2003, Linton 1999, Pile 1997). In this paper, the color system used to generate the color scheme is the NCS color model. NCS, Natural Colour System is a logical colour system which builds on how the human being sees colour. The system starts from six elementary colours, which are perceived by human beings as being "pure". The four chromatic elementary colours are yellow (Y), red (R), blue (B) and green (G), and the two non-chromatic elementary colours are white (W), black (S). All other colours can be described in terms of their degree of resemblance to the elementary colours[2].

The NCS Colour Triangle(Figure 2) is a vertical section through the colour space. Here you find different nuances of the actual blue hue R90B. The base of the triangle is the grey scale from white (W) to black (S) and the apex of the triangle is the maximum

Figure 1
Color Harmony Integration-oriented Design Process

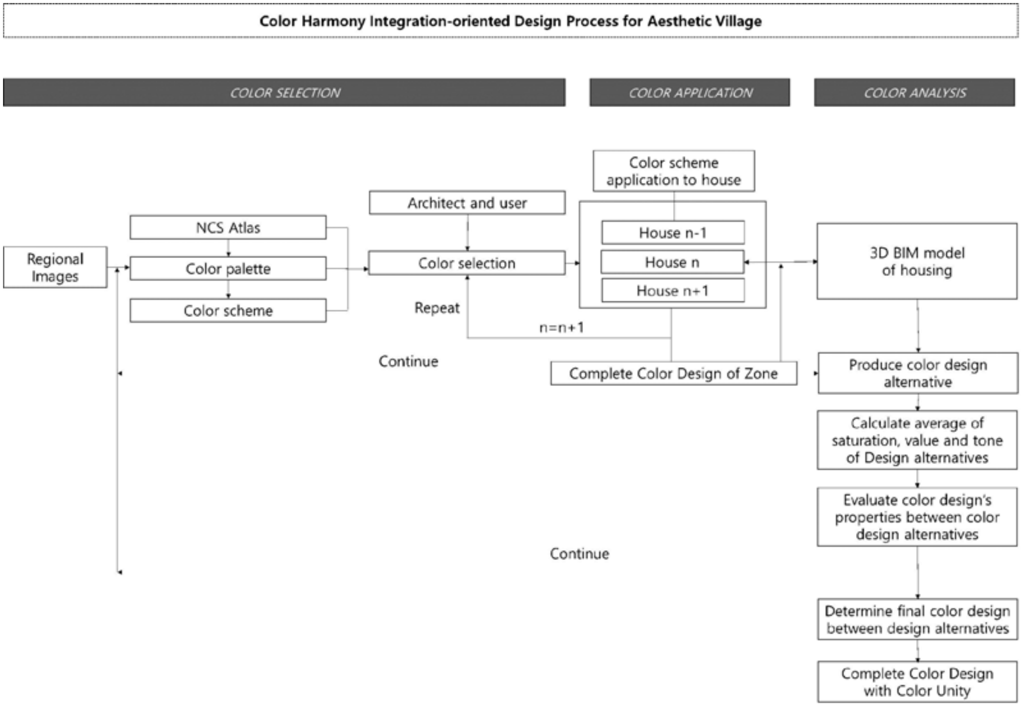
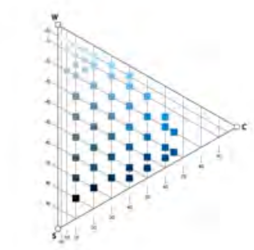


Figure 2
THE NCS Color Triangle



chromaticness (C) within each hue, in this case R90B. The chromaticness specifies how strong the colour is. Colours of the same hue can have a different blackness, chromaticness or whiteness values, which is different nuances. The scales for blackness, whiteness and chromaticness are divided into 100 steps, which as well as in the colour circle can be perceived as percentages. In the triangle is the nuance 1050 selected[2]. For example, S 1050-R90B, the notation of NCS, represents a Blakness of 10 and a Chromaticness of 50. The R90B symbolizes 10% red resemblance and 90% blue resemblance.

At this stage, one of the color schemes representing emotion is selected and color scheme is applied to the individual house. Figure 3 shows the color scheme(Manav 2017) derived by combining palette colors in conjunction with emotion. Color schemes were developed according to emotion. This study describes color schemes that can be applied to individual houses. How to apply the color scheme to individual house is a research issue to be covered in this paper. For example, a color scheme may be applied to a house as random, and it may be automatically applied by a computer as a way to unify the entire image of the village. Of course, the color scheme may be determined manually. When designing a village, choosing appropriate color scheme or color from the color palette is one of the most difficult challenges. Figure 4 is a color palette of the colors contained in the color schemes(McLachlan 2013). The colors in the color palette are represented by color models such as RGB, NCS, and Musell in order to improve the usability of colors. To create a color palette containing such information, it is necessary to convert RGB to Munsell code, RGB to NCS code. In this paper, we use a website[3, 4] that provides conversion services.

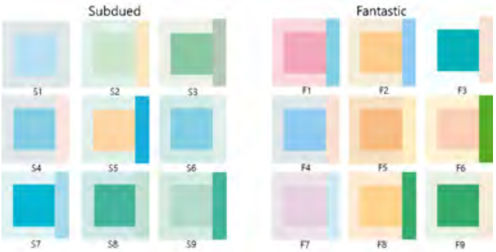


Figure 3
Color Schemes with Emotional Words

Step 2. COLOR APPLICATION

The second stage is the color zoning stage. A village can consist of several houses, but it can be made up of many houses. If the size of a village is large, applying color zoning to a village in order to realize color diversity and territoriality of the village can be an appropriate design strategy. This is because the landscape image of the village is greatly influenced by the color zoning. However, how to automate color zoning is not the focus of the research. Therefore, this study leaves the problem of color zoning to the architect. It is assumed that the architect applies the color zoning of the village to the BIM model interactively. The next task of color zoning is to apply color codes to individual houses by color zoning.

In this study, Autodesk Revit was used as a modeling tool for BIM modeling. The Table 1 shows Identity Data of the BIM Model(Karolina and Krzysztof 2018, Tonn and Bringmann 2018). The target village is a small island village located in Korea and modeled on a total of 90 households. Each house is consisted of a roof, a wall, and a window, and these three kinds of objects are subjected to color application. Houses consisting of three architectural elements are separated by House ID, and can be divided into zones for color scheme by grouping houses.

Table 1
An Example of Identity Data of BIM Model

Identity Data	
Blackness	5
Chromatic	40
Color	B10G
NCS Code	0540-B10G
Color Scheme	F1
M Angle	8.04
M Value	7.47
M Hue	B
House ID	1

Color attributes(Figure 5) of the NCS and Munsell have also added information to be handled in the color schemes. For the efficient input of these attributes, rule-based filters to visualize the color of the model is used. When NCS color code and color scheme are input according to the color scheme, the RGB values corresponding to the identity data prameter are output and visualized in the BIM model.

Step 3. COLOR ANALYSIS and EVALUATION

The color analysis step involves analyzing the characteristics of colors for design solutions (eg, Figures 6, 7, 8) generated through color assignment to the house. In this case, the color characteristic means hue, blackness, chroma, etc. in the case of NCS. In the case of Munsell, it means hue, value, and saturation. Design alternative 1 is a design created by a user applying an color scheme intuitively, and design alternative 2 is a design obtained by applying color of a color palette. Design alternative 3 is a design produced by unifying the colors of the roof based on the color scheme. Since the design alternatives are built on the BIM model, it is possible to automatically ex-

Figure 4
Color palette according to the color schemes

Color No	NCS Code	color palette	Blackness	Chromatic	Color	R	G	B	M Angle	M Hue	M Value	M Chroma	Color Scheme	Color No	NCS Code	color palette	Blackness	Chromatic	Color	R	G	B	M Angle	M Hue	M Value	M Chroma	Color Scheme
	NCS					RGB			Munsell						NCS					RGB			Munsell				
7	0540-B10G		5	40	B10G	118	220	255	4.64	B	8.04	7.47	F1	2	0530-B		5	30	B	142	212	255	8.45	B	7.89	6.92	S1
27	0520-R20B		5	20	R20B	255	156	176	0.54	R	7.14	9.41	F1	9	1005-B20G		10	5	B20G	222	238	241	0.86	BG	9.13	1.51	S1
28	0540-R20B		5	40	R20B	255	95	127	2.42	R	5.87	15.15	F1	14	0510-B50G		5	10	B50G	218	255	253	1.77	BG	9.62	2.75	S2
11	0540-B30G		5	40	B30G	124	242	255	9.56	BG	8.75	7.3	F2	19	0530-G		5	30	G	132	255	180	2.66	G	9	10.6	S2
24	0530-Y30R		5	30	Y30R	255	208	141	1.02	Y	8.37	6.95	F2	35	0510-Y40R		5	10	Y40R	255	232	208	2.13	Y	9.16	2.69	S2
33	1005-Y30R		10	5	Y30R	241	232	219	9.28	Y	9.06	1.49	F2	20	1002-G		10	2	G	231	241	235	1.16	G	9.27	1.45	S3
12	1050-B30G		10	50	B30G	93	227	241	9.51	BG	8.13	8.15	F3	22	1040-G		10	40	G	99	241	154	2.24	G	8.38	12.31	S3
13	0502-B50G		5	2	B50G	247	255	254	2.44	G	9.84	1.08	F3	24	2010-G		20	10	G	173	214	189	2.84	G	7.92	4.33	S3
33	0530-Y30R		5	30	Y30R	255	208	141	1.02	Y	8.37	6.95	F3	3	1005-B		10	5	B	220	233	241	6.09	BG	8.97	1.36	S4
9	1005-B20G		10	5	B20G	222	238	241	0.86	BG	9.13	1.51	F4	7	0540-B10G		5	40	B10G	118	220	255	4.64	B	8.04	7.47	S4
11	0540-B30G		5	40	B30G	124	242	255	9.56	BG	8.75	7.3	F4	26	0510-R		5	10	R	255	194	198	5.27	R	8.12	5.18	S4
42	1010-Y80R		10	10	Y80R	241	197	188	2.37	YR	8.61	3.66	F4	4	1050-B		10	50	B	84	182	241	9.98	B	6.66	9.45	S5
32	0510-Y30R		5	10	Y30R	255	237	210	4.56	Y	9.3	2.65	F5	14	0510-B50G		5	10	B50G	218	255	253	1.77	BG	9.62	2.75	S5
37	1010-Y40R		10	10	Y40R	241	220	197	2.68	Y	8.67	2.6	F5	36	0520-Y40R		5	20	Y40R	255	213	170	9.76	YR	8.56	5.06	S5
38	1030-Y40R		10	30	Y40R	241	187	130	8.99	YR	7.63	6.95	F5	7	0540-B10G		5	40	B10G	118	220	255	4.64	B	8.04	7.47	S6
25	1080-G30Y		10	80	G30Y	145	241	44	8.23	GY	8.45	15.44	F6	10	0520-B30G		5	20	B30G	182	248	255	7.66	BG	9.2	4.65	S6
34	0505-Y40R		5	5	Y40R	255	243	230	6.57	Y	9.51	1.55	F6	14	0510-B50G		5	10	B50G	218	255	253	1.77	BG	9.62	2.75	S6
40	0520-Y70R		5	20	Y70R	255	184	159	2.36	YR	7.77	6.54	F6	5	0510-B10G		5	10	B10G	214	244	255	9.21	BG	9.28	2.58	S7
1	0520-B		5	20	B	174	224	255	7.63	B	8.43	4.95	F7	6	0530-B10G		5	30	B10G	146	227	255	4.05	B	8.37	6.2	S7
29	1005-R40B		10	5	R40B	241	218	230	0.15	R	8.7	2.12	F7	8	1050-B10G		10	50	B10G	88	202	241	5.18	B	7.31	8.2	S7
30	1020-R40B		10	20	R40B	241	161	201	4.24	RP	7.14	8.48	F7	10	0520-B30G		5	20	B30G	182	248	255	7.66	BG	9.2	4.65	S8
23	1060-G		10	60	G	57	241	128	1.63	G	8.26	4.93	F8	16	0520-B70G		5	20	B70G	181	255	244	1.64	BG	9.37	5.17	S8
31	0530-Y20R		5	30	Y20R	255	219	144	3.41	Y	8.68	6.81	F8	18	1050-B70G		10	50	B70G	92	241	219	1.44	BG	8.52	9.35	S8
39	0510-Y50R		5	10	Y50R	255	227	206	9.95	YR	9.01	2.8	F8	15	0510-B70G		5	10	B70G	216	254	249	0.09	B	9.57	2.87	S9
21	1005-G		10	5	G	216	241	226	2.45	G	9.13	2.62	F9	21	0530-B70G		5	30	B70G	150	255	239	1.84	BG	9.21	6.93	S9
23	1060-G		10	60	G	57	241	128	1.63	G	8.26	4.93	F9	18	1050-B70G		10	50	B70G	92	241	219	1.44	BG	8.52	9.35	S9
33	1005-Y30R		10	5	Y30R	241	232	219	9.28	Y	9.06	1.49	F9														

Figure 5
Color Attributes of the House

House ID	Arch. Element	Color Scheme	NCS Code	Blackness	Chromatic	Color	M Angle	M Hue	M Value	M Chroma
1	Roof	F1	0540-R20B	5	40	R20B	2.42	R	5.87	15.15
1	Wall1	F1	0540-B10G	5	40	B10G	4.64	B	8.04	7.47
1	Wall2	F1	0540-B10G	5	40	B10G	4.64	B	8.04	7.47
1	Wall3	F1	0540-B10G	5	40	B10G	4.64	B	8.04	7.47
1	Wall4	F1	0540-B10G	5	40	B10G	4.64	B	8.04	7.47
1	Window1	F1	0520-R20B	5	20	R20B	0.54	R	7.14	9.41
1	Window2	F1	0520-R20B	5	20	R20B	0.54	R	7.14	9.41
2	Roof	F1	0520-R20B	5	20	R20B	0.54	R	7.14	9.41
2	Wall1	F1	0540-R20B	5	40	R20B	2.42	R	5.87	15.15
2	Wall2	F1	0540-R20B	5	40	R20B	2.42	R	5.87	15.15
2	Wall3	F1	0540-R20B	5	40	R20B	2.42	R	5.87	15.15
2	Wall4	F1	0540-R20B	5	40	R20B	2.42	R	5.87	15.15

tract color attributes for all the houses in the village. As already shown in Figure 5, the information contained in the BIM model includes house number, architectural elements, color scheme, blackness, chromatic, hue of NCS, color angle, hue, value and saturation of the Munsell. This information provides an opportunity to analyze and evaluate color designs from various perspectives. For example, the average of value and saturation for an individual house can be obtained, also the average value and saturation for the entire village can be calculated. Of course, the value and saturation of color of the architectural element can be obtained. In addition, the distribution of colors used automatically can be calculated.

Figure 6
Color Design Alternative 1

Figure 7
Color Design
Alternative 2

Figure 8
Color Design
Alternative 3

Table 2 shows the average color information for NCS and Munsell. As you can see in the table, there is little difference between the design schemes. However, the color distribution(Figure 9) shows a difference. This result is a simple average of the blackness(value) and chromatic(saturation) of all the colors used in the village. What is the significance of such a simple and implicit result? Is not there a way to improve the proposed color design because of the simplicity and the implication of these results? The answer to this question is that a simple and implicit result has a great implication in providing a reference point for controlling color attributes such as blackness and chromatic. In other words, because the average value of the color attributes can be calculated, lowering or raising the average value tells what color should be selected in subsequent design work. In the design of environmental color, blackness or chromatic value has a deep relationship with color harmony. Therefore, it is important to have information on the direction of color attributes in terms of color harmony. In the traditional color design process, it was almost impossible to know the color attribute value for the ongoing design, but it became possible to grasp this information in the intermediate process of the design in the BIM-based color design. In the conventional color design process, it is almost impossible to know the color attribute value of the ongoing design. However, in the color design process based on the BIM, it is possible to grasp such information in the intermediate process of the color design. Providing specific information on the evolution of the design is a great benefit of the BIM-based color design process.

However, the average value of the color attributes provides the direction of adjustment to the color choice, but does not provide specific information for the color harmony. One way to easily achieve color harmony is to create a color consistency. For example, unifying the blcakness and chromatic of colors or unifying hues increases the consistency of colors. Of course, unifying the color scheme used in color design also has to do with increasing color consistency. For example, to increase the color consistency, the deviation of the color attributes between colors should be minimized as much as possible. Limiting the number of color schemes used in color design can increase the color consistency. The higher the degree of color consistency, the stronger the identity of the architectural village. The color harmony integration-driven design process of this paper is a color consistency centered color design.

	NCS		Munsell	
	Blackness	Chromatic	Value	Chroma
Design Alternative 1	7.66	25.11	8.50	5.27
Design Alternative 2	7.30	22.21	8.59	6.17
Design Alternative 3	6.34	22.54	8.69	5.33

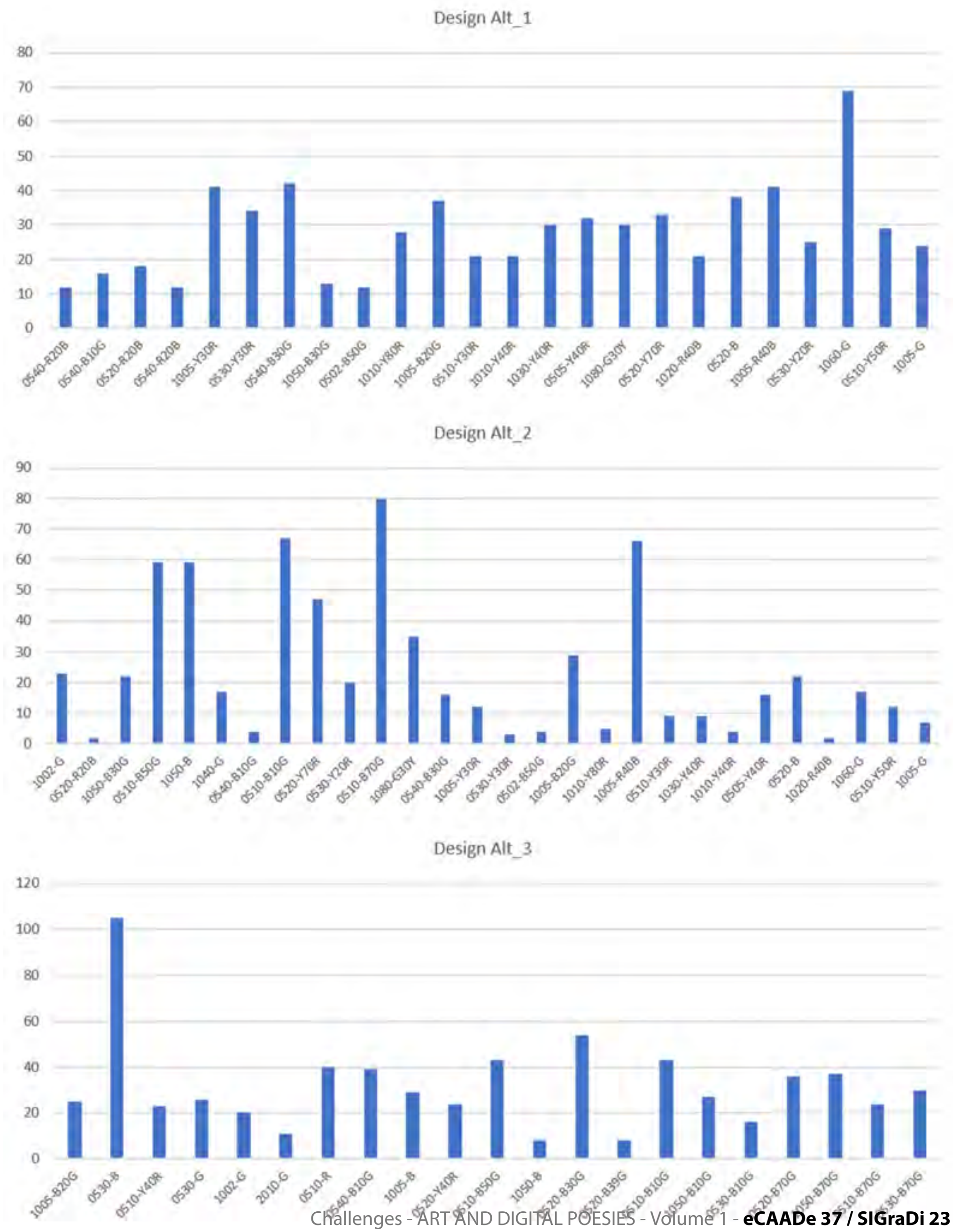
Table 2
Average Color
Attributes of Design
Alternative

- **DISCUSSION**

In this paper, thanks to the color design model based on the BIM model, a method of extracting color attributes has been developed. In addition, a method for analyzing the frequency of color and color schemes has been described. As a result, quantitative evaluation of color design can be made from time to time in the ongoing design process. In addition, the interactive color design became possible and the possibility of freely modifying the design was opened. Accordingly, the basis for improving the quality of color design has been established.

By applying color design methods, the color har-

Figure 9
Frequency of NCS Colors Applied in Design Alternative



mony can be achieved by increasing the degree of color integration, and ultimately, the aesthetic characteristics of the village can be achieved. This paper describes the analysis result of the design alternative and provides the basis for the architect to facilitate the final decision on the design alternatives. The contribution of this paper is to quantify the attributes of color design intuitively determined in traditional color design. Ultimately, this approach enables color design aiming at color harmony integration in the colorscape of the village. The final conclusion of this study is that the color scheme-based color design process enhance the quality of color design and the BIM-based color model provides an opportunity to quantitatively analyze color design solutions.

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Data - SMART CITIES

Grey Box City

Building cybernetic urban systems for smarter simulations

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In this paper we approach the concept of grey box model to understand the subjectivity and objectivity of urban design. From the beginning of the insertion of computational systems in the systems management, we understand that some simulations and the understanding of the city itself were partial: we do not understand the city and its spatial complexity and we have the pretension to do urban design thinking that we understand the urban life . Here we will address some categories of how we can simulate and create our urban systems using a more tactile cybernetics.

Keywords: *Grey Box, Cybernetics, Smart City, Information Technology*

INTRODUCTION

Many of the socio-spatial manifestations that take place in 21st century is organized by virtual and urban spaces interactions in a constant sensing surveillance between (Claudel; Ratti, 2016). Information is a fundamental element in this process because it connects these two spaces, formalized through signals and language systems that allow different actors to interact. These connections are important both in the predictability exercise (simulation and possibilities) and design (simulation and projects). With Information, we can have more than cognitive processes, we will be able to formalize the matter in complex ways, instrumentalizing the perception of information in a set of intelligent systems, conversing with physical space. In this paper we will address more about these connection processes using the cybernetic concept of a box.

For this, however, it is necessary to understand the process of the systematizations of the urban project. As cities and science there are several approaches (using the technical domain in its conceptual core) we can interpret the advent of technique as a means of expressing information. We understand this process in the technologies of Geographic Information System (GIS) and Information and Communication Technologies (ICTs) in geoprocessing urban networks, all of which are now recognized as tools of interaction and spatial agency. Cybernetics is important because it is the conceptual framework of computational technologies, where networks, design agents and the space talk and exchange information in the virtuality of cyberspace and cybercity.

"If a city can be seen with what is configured in space through exchanges of communication and transport of matter and energy, cyberspace can enhance and even complicate our vision and interaction with the space we inhabit. It can create community synergies, assist the planning and execution of joint designs, create effective channels with public authorities and, perhaps, reheat the real spaces through greater citizen participation. Networks can, and have already shown, serve as a vector for the empowerment of free and democratic communicative forms. " (Lemos, 2004)

Digital technology is an important paradigm in the intense flow of information because designers, planners and agents can have the ability to build a peer-to-peer, feedback-optimized systems to address city problems. The intelligent system, we can understand, is a system of intelligent agents that evolve and talk through feedback phenomena. Feedback is one of the important actions in a sustainable constitution of urban space, both in the efficient use of its resources and in the good maintenance of the system. The urban structures, to which these systems are attached, begin in this approach with the basic action of cybernetic mechanisms: input the information, which made all urban systems constitutions a planning conception. What we then constitute as a space in which we live is the result, through the cybernetic perspective, a cognitive apprehension that use informational processes: we interpret data, and we do the information, generating new information and new data.

The performance of design and planning, as Paul Pangaro says, is the intelligence to deal with the complexities that we generate of a systematization of several intelligent agents (Pangaro, 2015). The system is a design that seeks conversation. We have the greatest control when the conversation, confronting entropy, that is, the state of disorder of nature itself, is faced by the feedback process, the effort of what exists between the initial state and the modified state. Whether we are socialbiological, mathematical, linguistic, urbanistic or architectural, the tendency of a system always to tend to the nature entropy, and that must be reversed - generating syntropy by means different search for the own evolution. There lies the concept of intelligence inherent in urban systems. In this we consider that boxes, delimitations of scopes where the components form a joint characteristic, is a cybernetic system.

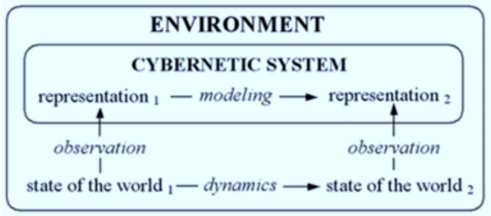

Figure 1
The Burtsev's Evolutionary Cybernetic System

On the urban scale we have some levels of analogous information developments in which we use cybernetics for building boxes. For systematization purposes, we will present relevant points of the cybernetic systems in the urban context exemplified by Claudel and Ratti (2016) and we will focus on what later develops as grey box, a model of performance and simulation. Boxes are strategies of analogies through which we construct strategies to perceive the complexities of systems, and use them as:

- Instrumentation: the ability of systems to measure information by means of sensing tools. It is the first movement of action against entropy. We consider this point as the principle of the movements formulator whether they are designable or not. Examples are locative media (LBM), georeferencing (GIS) and remote sensing. Environmental, energy, social and political sensors serve as parameters.
- Analytics: the form of see and interpret the information acquired are, in accordance with logic, the atribute of a analysis system. In an urban design, parametric methods are best known as BIM (Building Information Modeling), SIM (System Information Modelling) methodologies and the performance management (PM).
- Actuators: when the systems act physically in the agency of the city. Whether in planning, management or project assignments, the active systems that transform the city in real time or other deadlines are what architects generally relate to in the city's parametric management. Batch issues, use and parceling, templates, landscape projections,

and models of mobility and energy systems are some of the driving examples we will see below.

This information flow is an evolutionary process not very clear, a cognitive learning that lies in the intelligence of the city and its agents in the surveillance of urban systems. Sassen argues that technology can emancipate cities and citizens, and in this way, in a contrary surveillance, the process of constant activism of the systems before the flow can have different apprehensions and understandings that we can understand as a gray box, besides of their usual concept. The urban actions predicted here are locally referenced in the configuration of the events to which they are established (mobile, urban, modal or even architectural). These actions help us understand the complexity, that is, how the city structures itself in many other systems.

The systemic use of information in various city organs help us to understand both the organic spectrum of the whole (in governance and urban analysis) and the relations of different scales at the human level in the own urban experience (Sassen, 2010). In this perspective, we can also interpret that we must understand the system in how they are made in different ways at each moment, in a dynamism that goes beyond the assignments of a designer or a planner. In the view of Cybernetics we will configure the system capacity to generate new uses in an environment with conversation and simulation.

SYSTEMS AND THEIR COMPLEXITIES

The relationships made in design and spatial agency are communication structures, fed by information sources, to which planning form the basis of systematization cycle of urban design. Designs are traps of information (Flusser, 2007) that we deal with in logical structure that, in the urban context, has intelligence imbued by the city agents themselves (people, institutions, buildings, open spaces, etc.). This intelligence is the result of the ability of systems to go beyond the technical spectrum itself to an adaptive spectrum. This is the main complexity of systems and their flow of information, the challenges of facing a box.

Whether for sensing or design, any of all complex systems have intelligence as their ability to made feedback. This characteristic is what system makes assume a different and adaptive posture, depending on the environmental and informational conditions. This characteristic can be seen from the self-regulation of small computer systems to the GPS and cybersecurity, such as the Center of Operations Rio de Janeiro (COR). In this example, the system has geo-referencing inputs and then, during data interpretation and referencing, these data interact with other intelligent security systems and are measured by operators, creating an accessable database. Thus, this system constitutes a maintenance vigilance of the city integrated to other systems such as CET-Rio, Geo-Rio (to which we can understand GIS) and later institutions like community, the mobility systems and the government itself. These cyclical manifestations of action and reaction on critical data and visualizations are the very cybernetic informational fabric of urban planning and strategy policing (IBM, 2017) that we can gauge as instrumentalization and analysis of the city as a box, city box.

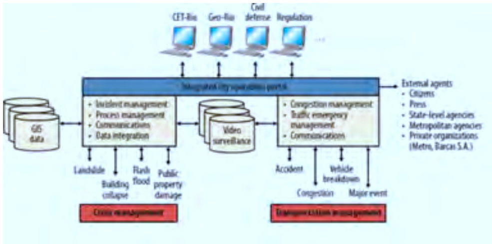

Figure 2
The Center of Operations Rio de Janeiro (COR).

We must always remember, in the first and second instance, that we are assessing the instrumentalization of the complex systems of the city as a cybernetic box. The box emerges as an analogy to a subjective characteristic inherent in urban analyzes, where the instrumentalizations of both people performance and physical systems are put into a database, transforming into parameters. These regulations, in the perception of city-box use, are a strategy today achieved in cases such as COR in Rio de Janeiro, Dubuque in the United States and Bornholm in Denmark, as well as certain urban development regions in the city of Beijing and its technological parks (Long, 2018). For these processes to take place and to extrapolate the objective visions of smart cities to smart systems, we will reflect more on how to open the systems and learn from themselves.

''Even if we manage to achieve such optimality with adaptive urban systems, caution must be taken. If we are considering only certain variables for optimization, it does not imply that we are solving a problem completely. [...] Integrating broader set of variables in the development of adaptive system requires the communication between all sectors of society. We are still in the exploratory process for finding efficient ways of achieving such communication and promoting social participation. This would certainly be necessary if we pretend to achieve optimal governance or sustainability. '' (Gershenson; Santi; Ratti, 2016)

Of course, by environmental factors (here not only referring to the natural environment, but also the urban environment itself) we would not be able to establish a possible connection of constant adaptation. Upon materialization this aspect is even less possible still. What we understand is that bringing only optimality, that is, in the strict sense of cybernetics that deals with the functioning of the system fully, would not have city systems over smart and complex agency. For complex systems, cities are unique because they have a large number of gray boxes: at the same time that we have knowledge of them, we will hardly have the ability to measure them or fully understand them by their inherent subjectivity. Thus, in the characteristic of a more actualized and less controlled vision, we will focus on those systems whose most visible aspects andevident aspects.

The case of the urban mobility structure in Zhuzhou in China, Autonomous Rail Rapid Transit (ART), allows us to understand the use of information sensing, feedback and then its new action (Yu; Kong; Yan, 2018). This process is continuous: ART evaluates information through sensing, performs its interpretation and then stipulates, through a critical analysis of the environment, a new performance different from the previous result or other information. This process later happens again, and so the continuity of this cybernetic loop makes the box-system evolve. Thus, not only in the urban system, but the design itself is also stipulated about these constraints: a design strategy where the designer himself has no knowledge of the box or its actions..

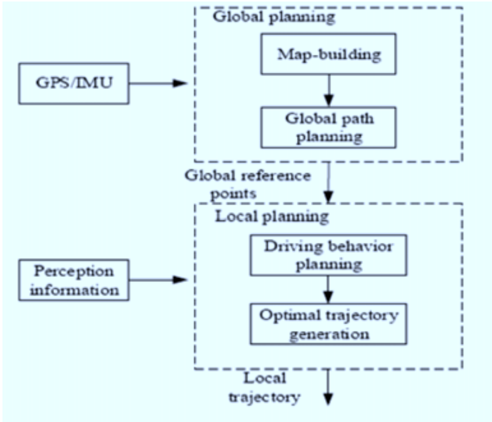

Figure 3
The Autonomous Rail Rapid Transit

The systemic concepts consider that the information constitutes the act of giving shape to the systems themselves. What we perceive is that cyclical processes of information apprehension, in the case of cities, uses smarter data analysis as a catalyst for the interaction between social agents and urban space (Lemos, 2004). We perceive this in the ART itself, which, by measuring a connection between the internal information (of the system itself) and external information (performance of human agents), transforms the direction and profile of the system itself. The intention of ART is to reduce the effort of several travel cycles to optimize certain uses of mobility, for which it constantly analyzes. This can be considered a cybernetic smart system that can be undertaken in other systems.

"Urban space today is pervaded by digital networks and systems, creating information that represents human activity. While most digitally managed urban systems generate operational data for their own purposes, they normally do not share those data directly with other systems or the public. As a result, digital information representing human activity in the city exists in many different places, locked within their specific domain." (Kloeckl, 2014)

As Kristian Kloeckl says, every human activity in urban space today has a willingness to be considered information in technological activity. The motto in this question lies in the connections these systems make, and how we deal with them. In the case of Kloeckl, the author analyzes that the interconnecting characteristic of a system and the constant feedbacks do not necessarily cause a destabilization, but make them more efficient from a direct performance point of view. We can address this technological development not only in mobility, but in other boxes that use the systems of analysis-performance in regions or urban agglomerations, areas of environmental interest as well as assemblages of urban traffic or even the expansions of the city, as shown by Beijing City Lab (BCL) research group on Beijing itself.

For the researchers of the BCL, it is necessary to understand, therefore, that the understanding of the system happens in a progression in which it depends on the sensing of equipments and people their due success. Systems are, to a lesser extent, dependent on each other. This statement lies precisely in the holistic characteristic that a system is greater than just its cartesian summation, and it is part of an environment. To clear the black boxes of the city, we need to answer - even if only partially - an urban question of how to bring cyber urban systems closer to human agency and people as a collective sense. Therefore, Cybernetics can become more useful.

BOX CITY

"For the discipline of urbanism, the struggle continues. Both of these trajectories present challenges in terms of infrastructure provision, housing, and socioeconomic development. But planners, policy experts, and economists are no longer the only specialists responding to these challenges. New actors enter the stage and bring new approaches to the field. Perhaps the most significant developments have happened in the domain of data-intense methodologies." (Offenhuber; Ratti, 2014)

The sociologist Bruno Latour in Science in Action proposes a broad confrontation that can help in how we can interpret the phenomenon of the complexity of the cities and the science that we understand like black box. We can use technology as a means of disinformation (Virilio, 2006), interpreting the project as a black-box incompleteness tool; or we may think we understand it fully. Digital technologies, by the very use of information that is out of control, can be black-box simulations and Latour understands that scientific complexity is a constantly changing field, and important information lies more in inputs and outputs and less in internal considerations of its operation and use, just as the strict black box is. But we need to try open the boxes.

Opening is not easy. The undersntading of black boxes allows you to extend the very structure that complexity can have. We care about feedbacks and inputs, and we look more sensitively at the behavior of the city compared to its systems and inhabitants. The algorithm is part of the systematization of the box, of course, where this system is integrated by the dynamic relationship with feedback (Claudel; Ratti, 2016), but it is only a look at its behavior. This look that escapes subjective control is the result of reactions and interactions that the systems, environment and individuals to which they are inserted in these free spaces suffer. If science and the urban design are treated as a power catalyst, we can see them as unfinished perspective of a clear, comprehensible white box and the then incomprehension of a black box model. The city is in a continuous autopoietic (Maturana way) evolution and the design simulation is a criticism about reality.

"The impossible task of opening the black box is made feasible (if not easy) by moving in time and space until one finds the controversial topic on which scientists and engineers are busy at work. This is the first decision we have to make: our entry into science and technology will be through the back door of science in the making, not through the more grandiose entrance of ready made science." (Latour, 1988)

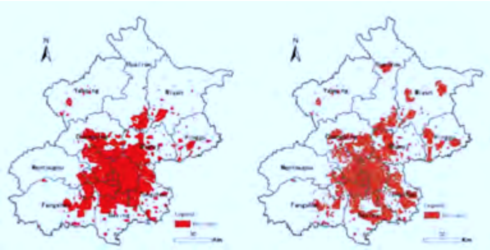

Figure 4
Simulations using the system BUDEM made by Tsinghua University for Beijing

The box strategy is a process of stimulate responses and conversations with the environment and the community. This process, of course, is an interpretation to which the observer is made before the system: a parametric process, for example, is more suited to a proposal of varied parameters (actuators) than a process of instrumentalization and remote analysis such as COR in Rio de Janeiro. Therefore, better the conjunctures of a city to understand its information, better we deal to the indeterminate information, eliminating stochastic structures. The positions follow empirical logic, it is not a question here of stricto sensu composing neither a programmed city simulation, but designers can and must use more information and informational means to deal with the demands and potentials we already know be of little control. One example of this is the use of stochastic and deterministic elements in the BUDEM system in Beijing.

The box city then becomes continuum between the aleatory and deterministic, permeating randomities stochastic equations of black box models and the deterministic logics of the cellular automata of the more transparent boxes. Urban analysis around black boxes has now become relevant now, especially with the development of AI as well as the progression in satellite data visualization and information and communication technologies, but it becomes problematic if used unilaterally. These progressions are important, of course, but we can influence ourselves more by taking advantage of other cybernetic studies as well as of ecology to understand more about the constitution of the gray boxes as a semi-transparent spectrum of problems, reflecting on the critical theory of the subjectivity of urban settlements and also of the sociology of space as a constant non-tree construction (Claudel; Ratti, 2014).

Far from the capitalist pretension that was promoted by smart city or the cold automatism of certain information devices (Costa, 2018) what we need to understand here is how grey boxes can help us in this city agency. We do not just need to computerize by creating algorithms for projects, but we need to interpret feedback from systems (input and output) and view information more in communities. We have already seen this mixed way of visualization and subjectivity in Senseable City Lab essays, like Real-Time Rome and, more recently, Gangnam Poop. In the Real-Time Rome project, for example, data visualization and information actions narrow the gap between spatial problems and representational problems that cybernetics could not previously achieve. These actions, metaphors of complexity and human subjectivity (such as a feedback between a Madonna's concert x texting) run away from the functionalist pretension of using digital technologies, which we have said before need to be refuted, since they are not fundamental but rather partial in systems of governance and development. The representation of information makes the communication of these systems themselves also an instrument of citizenship and citizen ownership of the use of digital technologies (Claudel; Ratti, 2016).

"Adaptive cities have the potential of increasing quality of life for citizens. But how equitable this increase of quality of life will be? Will all citizens benefit? At what cost? This is relevant, because even when cities accumulate most of the wealth of the planet, they are also the loci of greatest inequality. The answers to these questions will depend on how the adaptive urban technology is implemented, regulated, and managed in each city, and how this technology relates to citizens. This will require the effective interaction of governments, companies, academia, and society, as each sector may have different perceptions of the best way of managing cities.'' (Gershenson; Santi; Ratti, 2016)

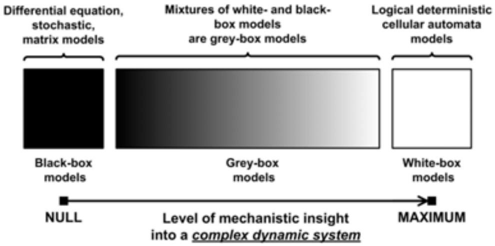

Figure 5
The complex dynamic system continuum

On these points Cybernetics needs to be an important but more actively interactive path. We still need to understand how to reduce the persistent noises in the conversations between objective systems and human systems involving urban characteristics (Offenhuber; Ratti, 2014). However, the information is in this act of informing and shaping, the basic constitution of our conversations, it is the inclusion of the potential dynamism design, action or planning the city. Today, artificial intelligence contained in parametric softwares for modeling and visualization of information is potential in this experimentation, tracing efficient and dynamic strategies in the result of urban actions, but we can move forward in bringing the subjectivity to a party of urban analysis. Here, then, we need to place ourselves as a bridge between the stance influenced by science as a narrative technology phenomenon and how we can look at the action practices of urban planners and architects in the face of the liberation of Cartesianism.

CONCLUSIONS

For designers or planners, the complexity of dealing with the subjectivity and the intense dynamism of cities enables us to create new strategies and approaches to get the subjetive information and use it correctly with the culture. This characteristic possibility of the urban systems, to enable formal-spatial strategies, are what lead softwares and technology to search correlations between the city information and their potentialities. This is a way, as described by Ratti and Claudel, of interacting with the contemporary city smartly and dynamically. It is the question of the of cybernetic planning, a dynamic interaction between agents and systems, in a systematization of monitoring and ecology transformation, natural or not (Claudel; Ratti, 2016), social or not. But, other question is: to what extent will we be cybernetically smarter?

''The connection between spatial and temporal scales evident in ecological processes may prove useful analytically to approach some of these questions in the case of cities. What may be negative in a small spatial scale or a short-time frame may be positive in a larger scale or longer time frame. For a given set of disturbances, different spatio-temporal scales may elicit different responses from ecosystems. [...] This raises a question as to whether a city needs a larger system in place to neutralize the impact on the overall city system of major disturbances within the city. [...] Unstable systems come to be seen as stable, bottom-up control turns into top-down control, and competition becomes less important. This also tends to suggest thinking of cities as the solution to many types of environmental damage. What are the scales at which we can understand the city as contributing solutions to the environmental crisis¿' (Sassen, 2010)

It is clear that the design isfaded to be imperfect and suffer other subjective issues, but in the teleological and technical consciousness we can make systems and cities more adaptive, and deal with evolutionary organisms, not stable organisms. A designer needs to establish cybernetic action in systems to create a network of communication and control. The persistence of an urban system is not necessarily stable but resilient. Researches in European cities such as Amsterdam and London show that the big-time agency and city-planning relationships between control agents and communication agents, users, demonstrate increased system efficiency in future participative design. We can verify that the structural systems with urban systems, parallel or not, create a dynamic network of different actors that proposes, at the same time, to potentiate spatial distributions of the city in an environment of distributive systems of information as well as to create a system of surveillance and control.

What would be the perspective of the smart city? Can we interpret them as data, measuring these elements in a hermetic way? No. Of course, we find evidence from Toronto to Sao Paulo, Amsterdam to Hong Kong, but we must interpret these examples as critical interpretations of the full urban experience as ways of interacting with the city systems. However, we can not fall into the stylistic forgiveness, translating as a remote sensing where parametric economic magnitudes can dictate the urban design. A cybernetic action in the city is an action where new processes of transformation and conversation take place, a more distributive dynamism, less centralized in the designer and more transpositive where it becomes increasingly important to mediate relationships for our community goals. The design process is in the communication between the constructed spaces, the virtual ones (simulation, virtual sensing) and the relation of the subject, being the use of cyberspace a connection point - dangerous - in this equation. What we must understand is that we should treat information as a process of formation and constitution of design beyond planning, neither as mere supporting data.

Digital technology in the city has been paradigmatic since its inception as a box, being able to modify how we see our intelligent organisms and our feedbacks. And this is not a purely building issue, it is the evolutionary and ecological answer of how we can integrate the complexity that we are facing with the digital information society. This discussion creates a theoretical path for new technological practices, and aims to establish a more critical research line forming the different framework on digital technology, representation, complex systems and design.

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Interdisciplinary design guidelines of an interface-device for a more accessible urban space.

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This work is part of the interdisciplinary research project ``Mediations of augmented space: artifacts, interfaces and representations in artistic and design disciplines", based at the Computing and Design Center of the Facultad de Arquitectura, Diseño y Urbanismo of the Universidad Nacional del Litoral (Santa Fe, Argentina), and directed by PhD. Arch. María Elena Tosello. The work, which was developed in the framework of a grant directed by MSc. Arch. Griselda Bertoni, proposes to reflect on certain limitations that may affect the experience of public space, and how, through the integration of artifacts, interfaces and augmented public spaces, a better appropriation, mobility and habitability of cities can be promoted for seniors. The work seeks to make a creative contribution so that older adults can exercise the right to mobility and feel active citizens of society.

Keywords: *design-driven innovation, augmented space, elderly, mobility*

INTRODUCTION

In our city, as in many other Latin American cities, public space has a structuring role. It is who configures the areas of pedestrian mobility in the urban environment, defining the quality of the city and, to a large extent, the quality of life of their habitants. In turn, the city is crossed by the phenomenon of virtuality, which is characterized by not requiring the physical presence of users for action, thus affecting the perception that people have of their immediate environment and the experience of public space.

Arroyo (2011) states that the experience of public space today is put into action from the event, from becoming, and not from continuity. The structure of public space must be thought of contingently, connecting elements, among which more the difference should prevail over similarity, producing multiplicity and significant ruptures. Thus, the street is not only the instrument for mobility around the city, but it is the place of manifestation. "The lack of spaces adapted to the requirements... of displacement over short distances (walking, biking, etc.), not only supposes a marginalization of this type of mobility that threatens the very essence of the city, but often entails the impossibility of displacement for broad groups of population" (Herce Vallejo and Magrinyà, 2013:22).

In parallel, the increase in the longevity of the population will be, according to the United Nations (UN), one of the most representative social transformations of our century:

- "... the aging of the population is about to become one of the most significant social transformations of the 21st century, with consequences for almost all sectors of society, including the labor and financial market, and the demand for goods and services (housing, transportation, social security), as well as for family structures and intergenerational ties." (UN, 2017)

According to data obtained from the World Health Organization -WHO- [1], it is projected that by the year 2050, 22% of the world population will be people over 60 years old, surpassing for the first time in history the age group that belongs to the children (0-14 years of age).

Thus, architects and designers in the age of the 4th Industrial Revolution are presented with the challenge of designing and constructing more inclusive interfaces, artifacts, buildings and cities that not only integrate older adults as active participants of society and beneficiaries of its development, but also incorporate the potential of emerging technologies as mediation tools. It becomes a priority, then, that the conditions of accessibility to urban environment allow the use and enjoyment in a safe and autonomous way of any person, regardless of their abilities and circumstances.

Our research aims to propose design guidelines for a system or device (Figure 1) integrated by artifacts, interfaces and accessible public spaces, which benefits the mobility of the elderly, improving globally the quality of urban life. A device is understood as a dynamic network that is established between heterogeneous and interdependent elements, which has a strategic function that responds to an emergency (Foucault, in Agamben, 2007).

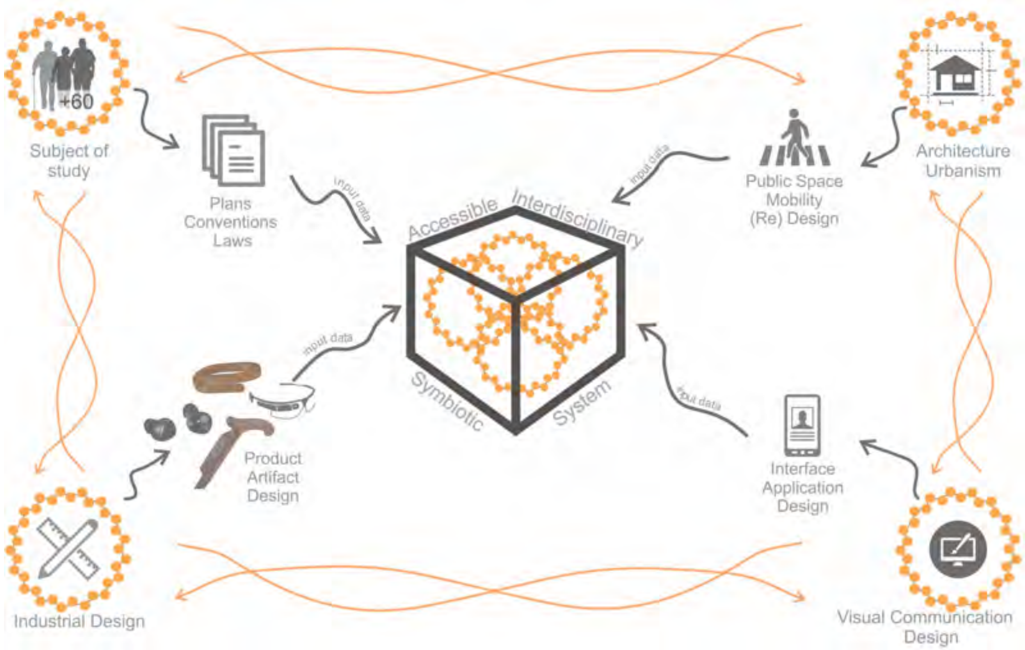


Figure 1
Diagram of the device.

METHODOLOGY

The research included different interrelated processes, not necessarily correlative.

Identification of the problem: this stage included the definition of the study problem; the analysis of its effects on subjects and practices; and the interrelation with other problems and contexts. Uses and appropriations of the urban public space were identified based on the incorporation of digital media in social practices; and the profile of the user was outlined, as well as surveys and interviews to record experiences.

Regarding the profile of the user, this is defined as an older adult "in the future", that is, they are people that today are between 40 and 60 years old, which in the next few years will become the new older adults. According to the investigation, the use of the mobile phone and the relationship with the digital media is foreseen to increase on this age group. In addition, it is assumed that the relationship they will have with technology will be different, more assiduous and familiar than the current one.

Background analysis and diagnosis: in this phase the categories of analysis were defined, and legislations, precedents, investigations and experiences with artifacts or facilities powered by digital media that have been integrated into public spaces were analyzed. Their impact and level of appropriation, the materials and technologies used, and their possible applications to facilitate accessibility and mobility in our city (Santa Fe, Argentina) were considered. There were also interviews with specialists, and a diagnosis was made, relating the problems with the available instruments, in view of possible solution alternatives.

New materials, technologies, artifacts (prototypes, projects, etc.), and applications (apps) were investigated, and public spaces in the city with the possibility of being integrated into the device were analyzed. In addition, background examples of smart cities were studied, and information on applications and technologies used to improve the mobility and experience of the city were recorded. It was taken into account that these cities not only made use of ICT to improve the quality of life of their citizens, but also they were part of the Network of Friendly Cities with Older Adults, belonging to the WHO.

Planning and design: the proposal of accessible (re) design of an urban space was developed and the design premises for the device were established. This device relates artifacts that record information, events, positioning or contextual conditions (a mobile phone + a headset, for example), with a control and management interface that communicates this information to users (application), in order to guide decisions, movements and / or actions in a previously conditioned area of the city.

RESULTS

The proposal links three disciplinary fields: Architecture and Urbanism -redesign of an urban sector-; the field of Visual Communication Design -definition of the features of the application and characteristics of the interface-; and the field of Industrial Design -definition of the functions of the artifacts to be incorporated in the device-.The design premises consist of guiding principles to achieve public spaces that are accessible and free of urban barriers, where pedestrian mobility is prioritized through proposals that promote safety, comfort and autonomy conditions.

Proposal description

In the field of Architecture and Urban Planning, some principles that according to WHO contribute to facilitate mobility were considered, especially the following recommendations:

- Environments adapted to pedestrians, with resources such as highly visible pedestrian crossings, raised surfaces or pedestrian islands; lower speed limits and measures to moderate traffic; well maintained sidewalks and cords (or curbs); overpasses and accessible underground passes; signs at pedestrian crossings with enough time to cross; and hearing aids in the crossings.
- Aesthetically pleasing elements in streets and parks, such as trees, gardens or vegetation.

- Numerous street crossings to multiply options, and adequate facilities for the elderly, such as places to rest and public restrooms.

The "groups" proposed in the guide of the Network of Friendly Cities with Adults, presented by WHO, were also considered. In particular, the suggestions in group 1 were observed, those that refer to outdoor spaces and buildings.

- The availability of places to sit down to rest is generally considered as an urban characteristic required for the elderly.
- Friendly sidewalks. The condition of the sidewalks has an obvious impact on the ability to walk in the local area. Narrow, uneven, broken, high bordered, congested or obstructed sidewalks present potential hazards and affect the ability of older people to walk on foot.
- Safe pedestrian crossings.
- Good accessibility. In many cities there are barriers to physical access that can discourage the mobility of older people.
- Adequate public bathrooms. The availability of clean bathrooms, strategically located, correctly signposted, and accessible for people with disabilities.

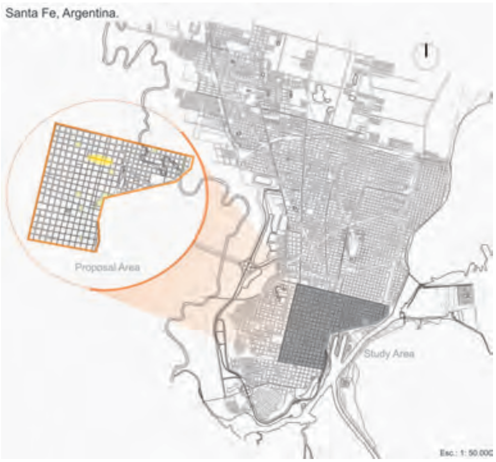


Figure 2
City of Santa Fe, Argentina. Proposal Area.

The proposal sought to create an augmented space that merges a good urban design (physical space) with ICT (virtual space), to achieve an intelligent environment.

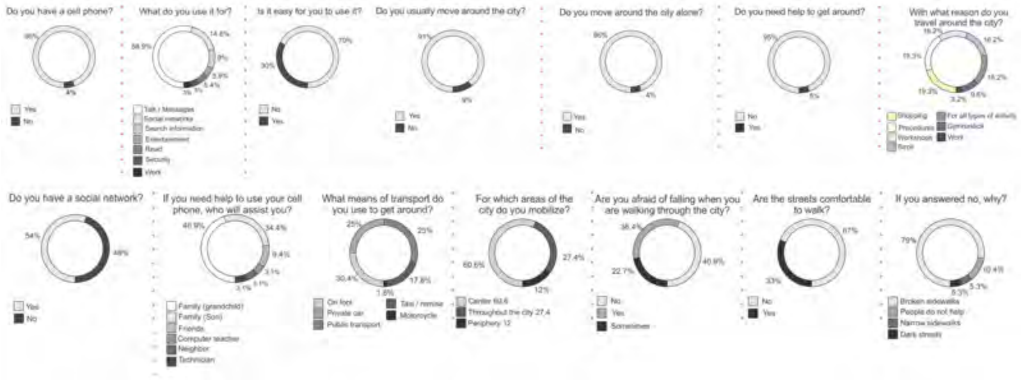
The urban sector that was going to be intervened was the result of the analysis of a first large area (macro center) delimited by streets and main avenues of the city (Figure 2). Within this sector, a survey was made of the urban services used by the elderly to carry out activities of their daily life (supermarkets, hospitals, clinics, cooperatives, pharmacies, banks, ATMs, etc.). At the same time, the monitoring cameras belonging to the City Government of Santa Fe were also surveyed, which would be useful for the project.

Finally, interviews were conducted with elderly people that are inhabitants of the city of Santa Fe. In the interviews there were two types of questions, some aimed at understanding what the relationship of the older adult is like with cell phones, and other questions related to the mobility in the city, to find out how easy it is for them to travel in the city, how they do it, why, and in what areas of the city they move. The interviews, which were anonymous, were made to 25 adults, all women, who attend various workshops (theater, memory, dance), belonging to the Retired Center "Nicasio Oroño" and the Retired Center "Banco Provincia" of the city of Santa Fe. The gender cut is because the workshops were attended only by women. The interviewees' ages ranged from 67 to 79 years, with an average of 72 years (Figure 3).

Four possible intervention sectors were selected, including one that has a greater number of public and private services, as well as one of the main streets of the city, with significant pedestrian and motorized displacements (cars, most bus lines, motorcycles, etc.).

The redesign of the sector, which incorporates in its premises all WHO recommendations, was made based on two categories that were established to encompass the proposed changes: one on the sidewalk-street relationship, and the other associated with the vehicular movement.

Figure 3
Diagrams of some of the information obtained in the interviews.



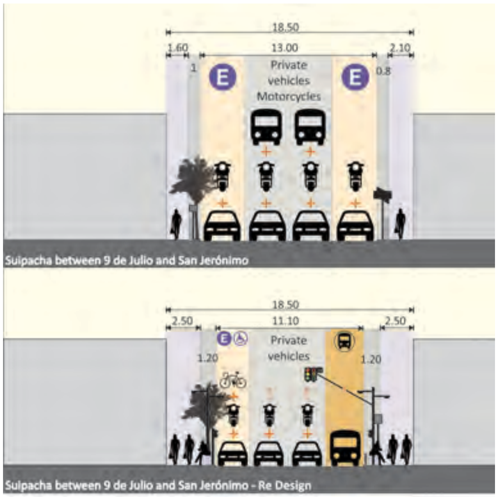
Proposals for sidewalk-street relationship:

- Eliminate the unevenness on the sidewalk, facilitating the safe movement of pedestrians in general, and of the cases studied in this particular research.
- Widen the sidewalks. It is expected to respect the free circulation volume of 2.00 meters wide by 2.20 meters high.
- Relocate trees, signs, gas boxes and traffic lights, to generate the space needed to meet the free volume of circulation.
- Incorporate street furniture, luminaires and public toilets.
- Incorporate both vehicular and pedestrian traffic lights with regressive numerical counter and audible signals for people with sensory disabilities.
- Provide good signage at pedestrian crossings, as well as the signs.
- Place tactile paving to guide people with sensory disabilities.
- Incorporate energy generating tiles in the descent ramps to sustain the system.
- Incorporate protective bollards.
- Place urban garbage dumps (with waste separation).
- Incorporate WiFi signal repeaters or extenders in the structure of existing elements.

Proposals related to vehicular movement (Figure 4):

- Eliminate parking in one of the street's sides, recovering that space for other non-motorized mobilities.
- Reduce the number of parked cars to promote pedestrian mobility and public transportation, as well as the use of bicycles (bike path projection).

Figure 4
Schematic cut of the sidewalk-street relationship.



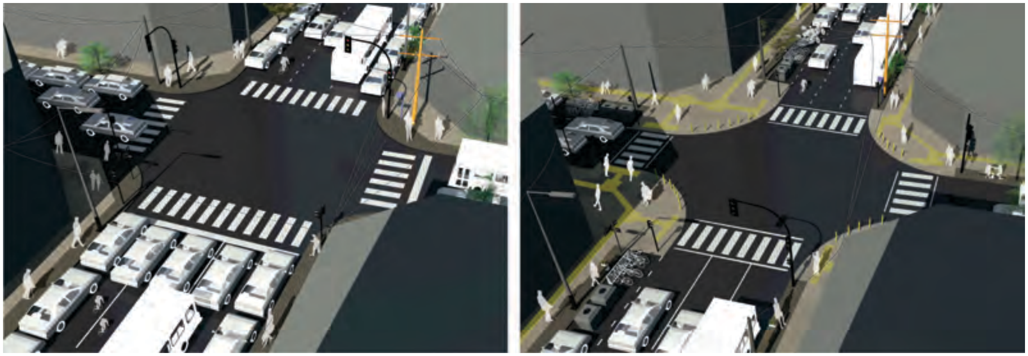


Figure 5
Redesign of one of the street intersections.

As an example, we present the redesign of one of the streets intersection of the area, since it is replicable both in the remaining intersections of the area, as in other areas of the city (Figure 5).

In the field of Visual Communication Design, the proposal consists of a multiplatform application that, among other features, provides users with on-demand information. "The evolution of information and communication technology (ICT) ...allows to manage and process huge quantities of data... The accessibility to this data opens up various possibilities to extract rich information about cities" (Morello, Carneiro, Desthieux, 2010:499). For this reason, the application will include an interactive map of the city with information about services and equipment that may be of interest to users, as well as information on the status and accessibility of the streets, following the same logic as Google Maps, OpenStreetMap, Maps.me, or other similar applications.

The application (Figure 6) will allow users to configure and edit their profile. In the configuration process they can select custom filters that will be processed by the application to provide information of interest for the user, when the latter is moving through public spaces. As in the scope of this research the subject of study is the elderly, it is assumed that the filters of interest of this type of user will be in relation to their basic needs (accessible routes and services such as supermarkets, pharmacies, workshops for the seniors, etc.). However, it is expected that the application will not only be aimed at the needs of the elderly, but will be useful to other age groups. Thus, users with different interests could suggest routes, provide circulation advice or share information about activities or events that take place in the city.

Figure 6
Possible functions of the application interface.

At the same time, the application is intended to link data sources that have been disconnected until now, gathering information that is already on the Web with information shared by registered users based on their own knowledge and experiences. This way, the active participation of users will ensure that the application is completed and updated in real time in a collaborative manner.

As in similar cases, the application will allow the user to have more control over the information, in order to deliberately perform tasks. A large part of the applications that were analyzed seek to adapt to the individual needs of each user. Also, they offer greater security, enabling the user to keep constantly in touch with their relatives or to know their geographic location at all times, similar to Family Locator and Life360. Therefore, in the configuration of the user's profile, two emergency numbers can be registered, enabling the option of sending these numbers to the user's location in real time through Global Positioning System (GPS).

Likewise, it will be possible to define mobility levels with the normal movements of the user and different ranges of information (range of immobility, speed range, range of inclination, range of vital signs, etc.). Also, in the event of any sudden variation in them (either because the user suffered a fall, a robbery or an accident), the application will alert emergency contacts. The alteration in the ranges can not only be warned to the emergency numbers, but the application can be configured to give an alert to other users who are close to the network in order to help the person who has suffered an accident.

Besides of the incorporation of the Web Content Accessibility Guidelines -W3C- [2], other recommendations to consider in the accessible design of web applications for the elderly [3] are the following:

- Information and operation of user interface must be understandable.
- Introduce product features gradually over time.
- Don't divide screens into multiple actions, one focus at once will have better results.
- Give clear feedback on progress and completion of actions.
- Provide reminders and alerts as cues for habitual actions.
- Use breadcrumbs or make it clear how to get back to the home page.
- No text overlaid on images or graphics.
- When using icons and symbols, always pair them with text.
- Simple plain backgrounds are better to avoid distraction.
- Make the purpose of the product clear.

Fonts:

- Allow people to adjust the text size.
- Avoid using multiple fonts.
- Avoid using condensed fonts.
- Use type weight to make a clear hierarchy.

Colors:

- Don't use color to convey a message
- High contrast is better. To verify that the contrast is adequate to guarantee accessibility, use the tool Accessibility Color Wheel [4]

Finally, in relation to the field of Industrial Design, different artifacts were initially investigated and considered to integrate the interface-device. Artifacts like a bracelet or a headset would operate in combination with the mobile phone (the support for the application), but would be used for communication with the user, understanding that both can give an adequate response in the event that the adult person suffers a sensory disability.

However, the first option (bracelet) was finally rejected because, due to vision problems typical of the age group to which the interface-device is intended, the headset is more practical. It is assumed that obtaining information verbally (by voice command), in general, is more useful than visually, since our user - the elderly - often suffers functional changes in the eyes that give rise to presbyopia (decreased ability to focus that causes blurred up close vision) or increased lens opacity. Although hearing loss is also common in these users, the headset in turn could function as a hearing aid.

Considering the projects of mobile phones that are in development, which anticipate the possibility of bending the mobile and becoming a wristband, it is expected that in the near future in the interface-device the use of another device (like the headset) apart from the mobile phone could be avoided, since all the functions would be integrated into the same artifact.

Following the planned functions for the headset, it will connect wirelessly with the application to verbally indicate the user the information available on it. In turn, the user will have the option to use the voice command to change the previously configured data at any time.

All wireless connections necessarily involve the availability of Wi-Fi service, which is why in order for the interface-device to work properly, extenders that amplify the signal could be placed. Beyond the fact that in Argentina the majority of mobile telephony services include data, the extenders would allow improving the signal of the City and / or State public networks, for the benefit of all the inhabitants of the city. These could be located every 200 meters in traffic lights or poles already located in the corners, for example, in the poles that hold the signage that indicates the name of the streets, thus no new elements would be added that could hinder the reading and experience of the urban space.

Based on the analysis of the artifacts that are currently on the market, it is feasible that the design of the handset allows it to be rechargeable with renewable energy by means of small solar panels, and something similar could happen with the extenders. The mobile phone could also be recharged by wireless power transmission. In this way, the entire system would be self-sufficient, not requiring traditional energy for its operation.

As the proposed interface-device emphasizes the information of daily character that the user can receive and not the artifact through which he will receive such information, the background idea is not to produce any new artifact, given that almost all the artifacts that we use on a daily basis allow us to receive information and feedback systems that can help others.

Design-driven innovation questions the reasons why people buy or use a product, and from there seeks to create market opportunities by proposing new meanings for the products (Verganti, 2009). According to Verganti "... radical innovations of meaning are rarely pulled by the market, they are pushed by a company's vision about possible breakthrough meanings".

The constant technological evolution allows us to use and resignify the artifacts according to the needs of the users, and thus, each individual adopts the type of artifact that is most useful, usable and desirable. In view of its appropriation, it is important that the interface-device assimilate these three characteristics in order to provide the user with a "brand experience" [5], which in this particular case focuses directly on improving its quality of life (Figure 7).

Figure 7
The quality attributes of User Experience (UX) as Utility, Usability, Desirability and Brand Experience [5], with Utility as the core.

The usefulness refers to whether the product really provides the user what he needs, and the usability responds to how easy and enjoyable is the set of features that the product offers at the time of use. Both are conditioned by the particularities of each user, and in this case, as it has been already mentioned, in the elderly, presbyopia and hearing loss are frequent, as well as the motor problems that cause loss of stability and other conditions that diminish the sensory and motor abilities of these users. In this sense, it is pertinent to remember that the universality of the design is based on its ability to enable products to be used by everyone, regardless of the circumstances and regardless of the platform or the device available to each user (cell phones, headphones bluetooth, glasses, watches and / or smart canes, etc.).

Regarding the desirability of the product, this will depend on the pleasure and well-being that the user feels when using it, and will be based on the quality of information, the capacity for personalization and the possibility that the user has to mold it according to his own experiences.

Based on the above, we propose a Minimum Viable Product -MVP- [6], a cross-platform network device that has defined the basic characteristics. Also, as it is being used the actions of the users are analyzed so that they shape the evolution of the system, in order to generate an innovation in the design driven by the User Experience -UX-.

Both UX-based design and desirability are linked to the "brand experience" that considers the emotions that a product arouses, since everything already mentioned has its corollary when the user feels and "connects" with the product. Exceeding the expectations of the user is the only way to achieve this purpose. Therefore, the system must go forward step by step to offer more accurate and personalized information, in order to reward the user for using the system, highlighting the value of its information with different contributions to transportation accounts, markets, taxes, etc.

To feed the interface-device (whether with information, energy or others), the City must also consider what is most useful, usable and desirable; for example, it could incorporate paving slabs to convert energy from people´s footseps (such as Pavegen System) in the most traveled urban sectors or 5G networks where antennas or sensors are available. Through Bluetooth beacons that connect to smartphones, piezoelectric tile systems can power off-grid applications - such as lighting, data capture and transmission, and environmental monitoring - rewarding citizens for their steps and generating a high commitment to convert their steps into energy and data.

The 5G networks work with small antennas distributed throughout the city, which, as already anticipated, must be incorporated by strategically choosing their locations so as not to visually contaminate the city. In order to contribute to the energy support of the interface-device, wind turbines can also be incorporated in avenues and spaces with high vehicular circulation. These urban turbines use traffic to generate electricity (Enlil Vertical Wind Turbines, for example).

Finally, we consider the IoT (Internet of Things) platforms for networks, which are the basis for interconnecting small electronic artifacts that monitor virtually any parameter. Smart cities use them to connect sensors, lights and meters that collect and analyze data, in view of a more effective and efficient use of resources. These data are then processed to improve infrastructure and public services. They can also be used to send emails or SMS messages alerting users when something needs attention [7].

By simplifying communications, these networks cause the low energy consumption device-to-cloud. Soon, there will be no need to replace or recharge batteries, since the artifacts will generate power on their own. Since some networks are compatible with Bluetooth, GPS 2G / 3G / 4G and Wifi, by combining connectivity solutions with each other, the user experience can be drastically improved [8].

CONCLUSIONS

Unlike the products that are under development and that have more sophisticated and complex technologies, the artifacts that make up the proposed interface-device are everyday objects (headphones, bracelets or canes), which incorporate technologies to provide effective solutions to daily problems. The functions of these objects are easily recognizable and they are controlled in an easy way, which is fundamental for their appropriation by the elderly. Furthermore, their aesthetic design seeks to adapt to a wide spectrum of users (universal design).

As the interface-device emphasizes information and not objects, our intention is not to produce new artifacts but to resignify existing ones, according to the needs of the users. The resignification of technologies, which proposes the creative reuse of knowledge, skills and available artifacts, is a phenomenon that characterizes the processes of technological innovation in Latin America. Innovation can lie in a combination of technologies, that is, in the establishment of relationships and interactions between dissimilar elements (Sennett, 2009).

To achieve this purpose, it is relevant to consider the design of the application interface that articulates the relationships between the elements that are combined, since the less complex the procedures are to obtain information, or the less interactions, requirements or steps are necessary to reach the objectives, the better conditions will offer the device to the elderly.

The interface-device consists of a networked system, self-sufficient and constantly connected, where data and information are transmitted as well as energy, to provide security, comfort, guidance and decision-making power to users. Therefore, our proposal would not only benefit the elderly, but could be used in other applications such as wayfinding, for example. Wayfinding studies information communication systems that facilitate the orientation of people to improve understanding and experience of space (Lynch, 1960), and focuses on a non-standardized user profile, considering a diversity of capabilities and physical, cultural, social, etc. variables, in relation to a specific context.

In the dynamics that characterize the current world, information is the actor that gives decision-making capacity and autonomy to users. While users are well informed of what happens in their immediate environment and they know its characteristics, the more accurate decisions they can make when they move around the city.

In most of the cases that were analyzed, architecture considers passive solutions regarding the problem of accessibility to the physical environment. However, an accessible design should not be thought only with passive elements, but incorporating instruments of mediation of augmented space. Therefore, we will be creating smart cities in which the promotion of mobility is not only contemplated by a good urban project, but guaranteed by the convergence between the physical, the biological and the virtual.

As future work, we will deepen the study of alternative energy generation systems, such as the aforementioned piezoelectric tile systems, Enlil wind turbines, or networks like LoRa and Sigfox. Also, we will consider financing lines and possible ways to manage the project for its development.

Finally, we understand that the complexities of our globalized and connected world cannot be solved in isolation. A single professional no longer has the capacity to solve a problem on its own, but rather interdisciplinary groups and collaborative and participatory design processes are needed to address the problems of 21st century habitat.

ACKNOWLEDGEMENT
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Citizen Engagement through Design Space Exploration

Integrating citizen knowledge and expert design in computational urban planning

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A common understanding exists that citizens should become more involved in the design, planning, and governance of the city. Due to a lack of common platforms and difficulties in the meaningful integration of the participatory input, however, the tools and methods currently employed in citizen engagement are often ill connected to the design and governance tools and processes used by experts. In this paper we describe a Grasshopper and Rhino based approach, which allows designers to share a subset of the design space formed by parametric design variants with citizens via the online interface Beta.Speckle. In a user study we evaluated the usability of the tool as well as studied the design choices of participants, which were found to be influenced by preferences for visual order and underlying economic, social, and environmental values. For the future design of participatory exercises, it was concluded that indicators relating to citizens' values and preferences will allow for a more effective exploration of the design space and increase the meaningfulness of results.

Keywords: *design space exploration, citizen engagement, parametric urban design, computational urban planning, space matrix*

INTRODUCTION

A common understanding exists that citizens should become more involved in the design, planning, and governance of the city. However, although citizens are often consulted, it was found that their contributions are rarely employed and considered in planning and decision making due to a lack of integration of engagement activities into the planning process itself (Hasler et al. 2017). The development of engagement tools that allow for a better integration into existing planning and governance practices has consequently been described as a challenge in the field (Ertiö 2015).

Especially in the development of urban design projects, citizen engagement is very often limited to gathering feedback on or informing the public about

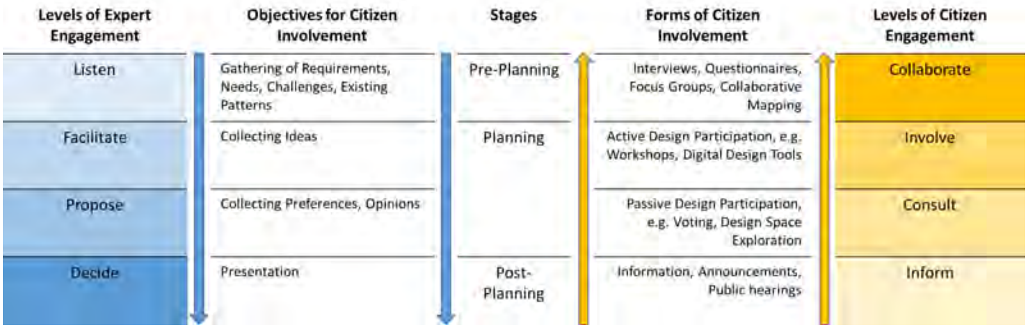

Figure 1
Mapping of the relationship between expert involvement and objectives for engaging citizens in different planning stages (see Brody et al. 2003), as well as the forms and levels of citizen involvement and engagement [1] in design and planning.

finished design proposals rather than involving citizens more actively in the design process (Klosterman 2013). Parametric design has been hailed as a useful tool to help bridge the gap between experts and laypeople and support citizen participation in the urban design process (Steinø et al. 2013).

In this paper we describe a Grasshopper and Rhino based approach, which allows designers to share a subset of a parametric design space with other stakeholders via an online design space exploration interface called Beta.Speckle [6]. This paper further presents the results of a user study, in which the approach was tested and feedback on the usability of the tool was collected as well as the reasons underlying specific design choices were evaluated. This paper concludes with a discussion on how the integration of citizens in urban planning via parametric design space exploration can be better curated and explores the impacts on the design process from the designer's perspective.

BACKGROUND

The engagement of citizens allows to integrate important local and community knowledge into the planning process, which can improve the quality of designs as well as the relevance of decisions to the community (Sanoff 2006). Therefore, the involvement of citizens in urban planning and decision-making processes has been considered a requisite, but its objectives, the information that is provided to citizens, the stage of the planning process citizens can get involved in and the techniques that are used to do so vary widely (Brody et al. 2003) (see figure 1).

In the past decades, the advancements in information and communication technology (ICT) have led to the development of new digital tools to complement more traditional participation methods, such as face-to-face meetings and workshops, focus groups and surveys (Kleinhans et al. 2015). One of the earliest examples of digitally enabled participatory design is that of PARTIAL, a parametric CAD system devised by Robert Aish and Jan Fleming in 1977. PARTIAL provided a context in which both professional designers and the end-users could collaboratively design and evaluate a particular building typology. Specifically, it consisted of a space-planning drawing interface that was accessible by both architects and lay persons. As the end user would evolve her or his design, it would be simultaneously evaluated by a certain set of criteria that were relevant to the typology itself (noise, accessibility, lighting). Nevertheless, the evaluation was not meant to trump human judgement, but augment it: *"[PARTIAL] provided a context where the designers/participants could combine their own subjective design ideas with the necessary technical requirements"* (Aish and Fleming 1977).

In 1977, PARTIAL could not leverage the potential for outreach offered by the internet, as it did not exist; consequently, its users needed to be co-located physically with the computer itself. The advent of web-based tools for public participation in recent years has allowed to address and reach a larger and more varied audience (Bizjak 2012). Web-based engagement applications include so-called public participation geographic information systems (PPGIS), such as Maptionnaire [2], which allow to collect information on existing needs and challenges through participatory mapping and have been employed in the preplanning stages of urban design. Online 3D modelling applications, such as Minecraft [8], have supported the active involvement of citizens in design and planning projects.

Also, planning support systems for expert designers have moved towards web-based services in recent years. Existing Grasshopper (GH) plugins and related applications that support the online viewing and sharing of parametric models and design spaces can be distinguished into three categories: web-based viewers, web-based collaboration platforms, and plugins connecting to other existing online visualisation and mapping platforms.

GH plugins in connection with custom web-based viewers and services primarily allow the sharing of parametric models and design spaces with stakeholders. In this category belongs ShapeDiver [4], which has found its main application area in providing online product configurators on websites. More advanced online interfaces for the exploration of parametric design spaces additionally provide means to filter or strategically traverse the design solution space. Examples include the Design Explorer (Thornton Tomasetti 2015) as well as the Design Space Explorer (Fuchkina et al. 2018). A different type of application in the field focuses on connecting to and visualising parametric models on existing online platforms, such as the plug-in Giraffe (Leung et al. 2019), which allows to visualise and interact with geo-located parametric models in Mapbox [3].

GH plugins and toolboxes for online within or across platform collaboration help establish communication and collaboration workflows to support design and development processes in the architecture, engineering and construction industry (AEC). An example of such a platform is Speckle [5]. It posits itself as a data platform for the AEC industry that facilitates design communication and coordination. Currently, it offers several software specific integrations that allow data ingress and egress from GH, Dynamo, Rhino, etc., as well as management and coordination functionality. Speckle's online viewer, similar to other solutions, serves as visualisation and communication platform for exchange within design teams but also with other stakeholders from non-design related domains.

Although web-based applications and platforms for citizen engagement in urban design and those supporting design collaboration, visualisation and sharing in AEC pursue similar goals in as such that they try to engage and connect different stakeholders in the design process, the connection between the two has to the authors' knowledge not been tested before. In this paper, we therefore present an approach that positions the use of online DSE applications in citizen engagement as a way to facilitate participation in urban design.

MATERIALS AND METHODOLOGY

In the scope of a user study we tested the applicability of the existing design space exploration tool and GH plug-in Beta.Speckle [6] for citizen design engagement. For the user study we implemented a design exercise, which provided a set of design alternatives for the development of the neighbourhood next to the upcoming Cantonment MRT station at Tanjong Pagar in Singapore. The exercise formed part of the "Ideas for Tanjong Pagar" study [9], which provided a platform for the testing of several online exercises (see also Tomarchio et al. 2019).

The Design Space Exploration Application Beta.Speckle

Beta.Speckle [6] is an early version of the more advanced Speckle platform [5]. It consists of a set of GH components and an online viewing platform, which allows to explore a range of pre-computed variations based on a set of input parameters that can be ex-

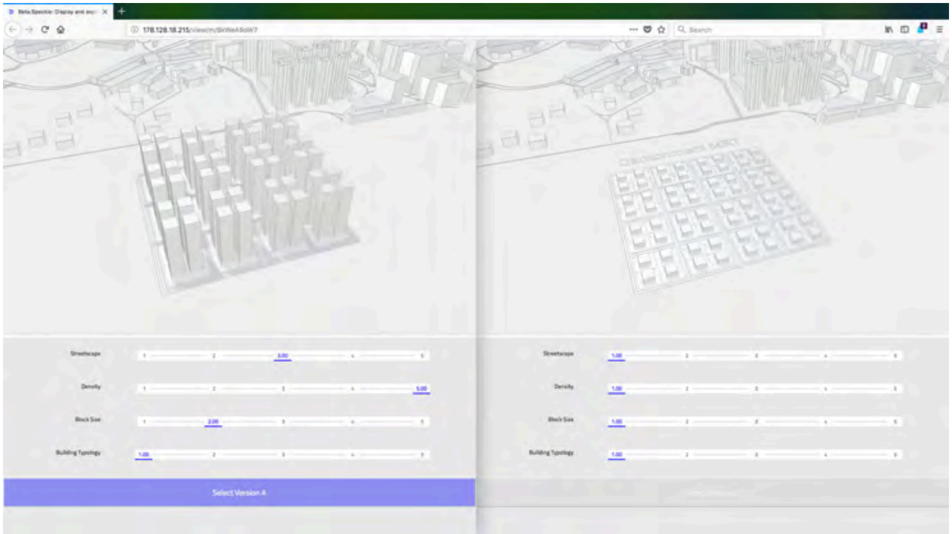

Figure 2
The DSE
Beta.Speckle
application and
exercise.

plored choosing different options on a slider-like input mask. Although Beta.Speckle allowed to export and display coloured meshes, we decided to use a plain model for a higher performance of the application. For the study, the online interface provided a comparative view, which allowed to compare two selected designs side by side (figure 2).

The Design Exercise

The design exercise consisted in the choice of a preferred layout for the site next to the new Cantonment MRT station. The underlying parametric model allowed to explore layout variations, which were derived from SpaceMatrix characteristics (Berghauser-Pont and Haupt 2010) and included variations in building intensity, i.e. the floor space index (FSI) or gross plot ratio (GPR), in network density (Nf) and street profile width (b), as well as of coverage, i.e. the ground space index (GSI). Participants were presented with the following parameters for exploration:

- **Streetscape**: the profile and width of the main streets, from pedestrian friendly neighbourhood street to cycling friendly main street to public transport boulevard.
- **Block Size**: the amount and size of urban blocks in the neighbourhood.
- **Building Typology**: the typology of the buildings, from point, row to block buildings.
- **Density**: the density on the site, i.e. the amount of floor space available for people to work and live in the neighbourhood.

Participants could vary the layouts by choosing one of five options for each of the four parameters (see figure 3). In total, the model thus provided 5^4 = 625 design variations. The options for building typologies were based on Martin and March (1972 in Berghauser-Pont and Haupt 2010, p. 172) and included a point or tower typology; strip or row housing; and court or block types. The streetscapes ranged from neighbourhood and main streets to boulevard profiles, which could be distinguished by their varying number and arrangement of car, bicycle, and public transport lanes.

The design space of the model is depicted in the SpaceMatrix diagrams for FSI and GSI as well as Nf and b in figures 4 and 5. The urban layout variants are clustered in five vertically distributed bands, which are determined in the first diagram by the density and in the second by the block size. The profile width of the five streetscape options determines the horizontal distribution of the design variants in figure 5.

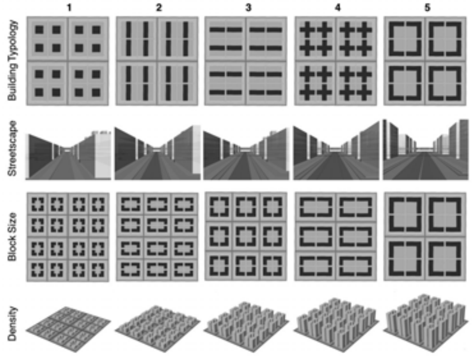

Figure 3
Overview of the design parameters and options, which form the solution space of the parametric model.

Participants
Thirty-two participants (16 female, 15 male, 1 other) took part in the main study, which took place in June 2018. The majority of participants were bachelor or master degree level students (29 out of 32) and had no background in urban planning (31 out of 32). The average age of participants was 24 years.

Study Set-Up and Data Collection
The user study was organised in groups of up to four participants. The DSE exercise was completed as one of three exercises in varying order, with the other two exercises based on the Quick Analysis Kit (Mueller et al. 2018). Prior to the start of the study, the exercises were set up as tabs in Google Chrome on laptops.

After a short introduction, participants were asked to first explore the different urban design propositions provided by the application and to then submit their preferred layout for the site. The instructions deliberately left room for interpretation to understand the decision and meaning making processes underlying the selection of a specific design proposal. The exercise took about 10 minutes to complete. After submission, participants were asked to fill in a questionnaire. The survey consisted of a mix of open and closed questions, which asked for user feedback on the design choice, the application and exercise, as well as for demographic information of participants. To evaluate the usability of the tool, we employed the system usability scale (SUS) developed by Brooke (1996). It has been widely applied, as it is technology independent and reliable, easy to use and to understand (Brooke 2013).

RESULTS
This section presents the results of the user study, which include an analysis of the selection of design variants and the underlying reasons for specific design choices, as well as an analysis of the usability of the application, the user experience and an overview of participants' suggestions for improvement.

Selected Design Variants and Reasons Underlying the Choice of Specific Parameter Options
The participants submitted a total of 30 unique preferred design variants, which spread over the design space of the parametric model. The distribution of the chosen options for each of the four model parameters can be seen in figure 6.

Analysis of the collected qualitative feedback elicited different motives and reasons for the selection of specific parameter options. Reported considerations in respect to density fell primarily into two categories: either participants selected high density and high-rise options (4 or 5) in response to the Singaporean challenges of land scarcity and increasing population size, or they selected moderate density and low- to mid-rise options (2 or 3) in response to the context with similarly, moderately dense areas to the north of the site. The majority of participants (18 out of 32 votes) decided for the latter further citing aspects of spaciousness, comfort and liveability underlying their decision in favour of the low-rise option 2 and the balance between density and spaciousness, considerations of natural light and shading, natural ventilation and urban heat island effect (UHI) in the case of density option 3.

In respect to the building typology, analysis of submissions found a preference for perimeter blocks (option 5, 12 votes) and point buildings (option 1, 10 votes). Point buildings were selected for their perceived aesthetic appeal and associated with sophistication, timelessness, and simplicity: *"The square-ish type building shape (1) that I have selected will be timeless, so the design of the buildings will not pale in comparison to the fast-paced development of the neighbouring district."* (P18)

Layouts with point typology were perceived as less crowded and cluttered, as more familiar, better

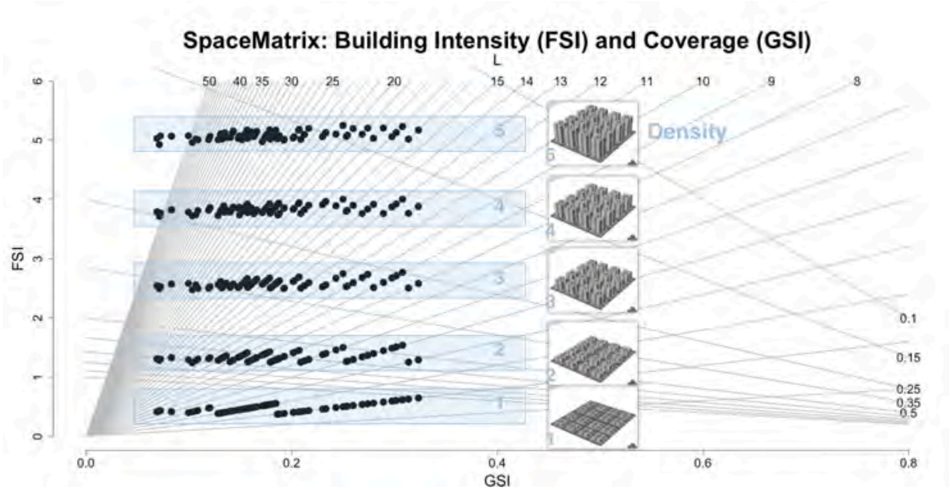

Figure 4
Distribution and design space of the model and its generated variations plotted in the SpaceMatrix diagram for building intensity and coverage. Five vertical bands are distinguishable, which represent the five density parameter options.

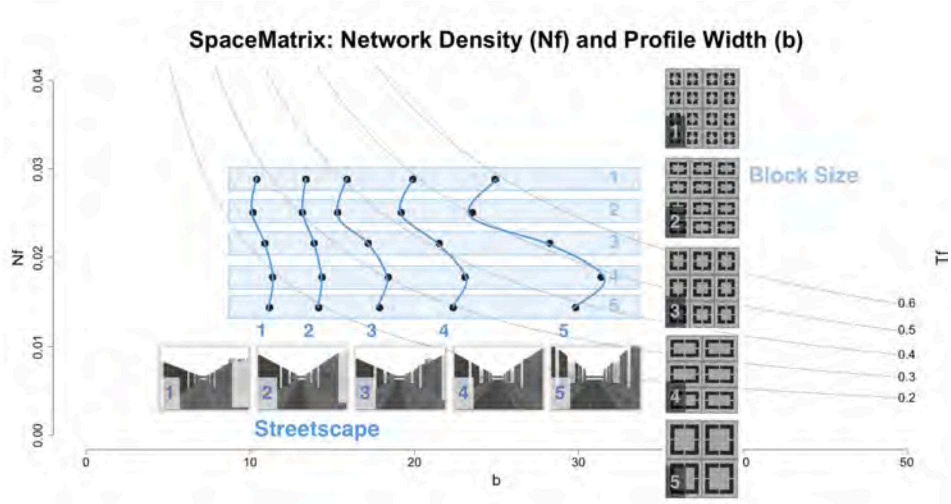

Figure 5
Distribution and design space of the model and its generated variations plotted in the SpaceMatrix diagram for network density and profile width. The five block size parameter options are distributed in five vertical bands, whereas the five streetscape options form horizontal bands.

fitting in with the context and more organised. Block buildings were selected because of the public spaces they enclosed, which could serve as communal areas and host playgrounds, fitness and sports facilities, and because of the perceived opportunities for neighbourhood interaction that could ensue. Strip buildings were chosen because of their orientation and directionality, either facing the MRT (option 2, 4 votes) or facing the CBD (option 3, 3 votes). The form was also considered to allow for more natural light entering the building. The plus-shaped typology (option 4, 3 votes) was primarily chosen for its uniqueness in form and the possibility to connect the buildings via skybridges.

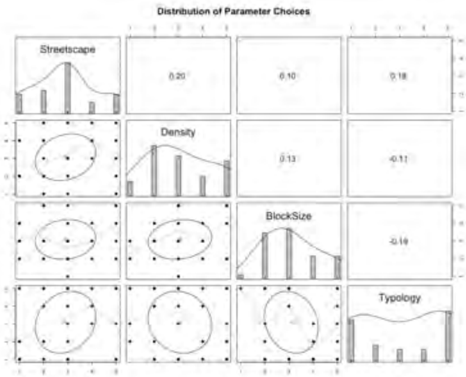

Figure 6
Distribution of chosen options for each of the four model parameters and correlation between parameter pairs.

Participants based their choice of a specific block size on the number of resulting buildings, the impression of spaciousness and the resulting amount of green and open space. Larger block sizes resulted in less buildings (options 4 and 5, 5 votes each), which were associated with a larger central area within or between buildings and reduced complexity of the layout, and was expected to support navigation. However, the majority of participants chose options 2 (10 votes) or 3 (11 votes) offering medium block sizes, which were still associated with an acceptable degree of spaciousness, but were considered to provide a better balance between built up and open space: *"There has to be a balance in between optimum land use, social coherence, space openness and street spaces, which remained the basis for this design."* (P31)

In the choice of a streetscape, participants took into account the profile width of the different options as well as expected traffic flow and density, perceived walkability and accessibility, as well as the amount of space consumed. Streetscape option 3 received the highest number of votes (13 votes), as participants tried to achieve a balance between different spatial, mobility- and traffic-related considerations.

Narrower streetscapes, such as options 1 (5 votes) and 2 (6 votes) were associated with better walkability, comfort and liveability, whereas the wide streetscape of option 5 (5 votes) was associated with easier navigation and with the greater distance between buildings allowing the street space to be used for other, temporary functionalities, such as street malls and parades.

Usability of the Tool, User Experience and Suggestions for Improvement

As stated before, participants were asked to evaluate the usability of the tool according to the SUS. The SUS returns a score in between 0 and 100, which does not represent percentages but percentiles. The usability of the application was rated at 66, which is situated in the second quartile, at the lower end of acceptable in the acceptability range and in between the adjective attributes of 'ok' and 'good' defined by Bangor et al. (2009).

Although participants found the application easy to use and easy to learn, a time lag in loading the model between parameter changes affected the user experience and efficiency of use. Participants perceived the time lag as disruptive, inhibiting the workflow. Furthermore, the participants discussed the usefulness of the exercise critically. They felt the depicted design was very generic and repetitive, and thus did not address urban design in its complexity. In respect to the set-up and framing of the exercise, participants mentioned they would have required additional contextual information and clearer instructions.

Furthermore, the tool was perceived as a tool for expert users. Participants found it difficult to envision what the proposed designs would look like in reality and to understand what the design parameters meant and how they affected the design. Also, they could not discern differences between some of the options and would have required explanations of individual parameter options. Furthermore, they felt that the linear scale misrepresented the functionality of the interface element and the relationship between the different options, which did not actually constitute a continuous scale, but a selection of discrete values. In respect to functionality, participants commented negatively on the lack of variations in the designs and the limited choices. The lack of creative freedom was perceived as a shortcoming and a limitation of the tool.

Accordingly, participants suggested improvements, which regarded the design representation, the user interface and functionality of the tool. Participants strongly suggested using colours for the model and letting users explore the model from an on-ground perspective rather than the bird's eye view, as this could help to make designs more accessible to non-expert users. They further suggested to provide more detailed explanations of the parameters and their impact. In respect to the functionality, participants suggested to increase the level of creative freedom by allowing buildings to be adjusted individually or to be moved freely on the site.

DISCUSSION

The feedback collected during the user study shed light on the preferences and values underlying design decisions of participants. As had been previously established by Gjerde (2017), visual order was also found in this study to be an important factor underlying participants' choices in respect to urban arrangements. This manifested itself in the avoidance of perceptually cluttered and crowded designs and in a preference for more visually organised and balanced proposal; organised in respect to the choice of simple, point typologies and balanced in respect to the visual balance between built up and open space. Aspects of visual order also underlay the preference for proposals with a reduced level of complexity regarding the number of buildings and resulted in the choice of specific density values to allow for a consistency in height in relation to the urban context.

Participants' decisions were further based on values and expressed themselves in the choice of a solution or option, which was perceived to uphold these. Value categories found in urban development are economic, environmental, or social in nature (Friedman et al. 2008, p. 11). In our user study, economic values manifested themselves in considerations related to land scarcity and land consumption leading to the choice of higher density options. Environmental values surfaced in form of considerations related to the sustainable development of the site aiming to capitalise on solutions providing natural lighting, shading, and ventilation and reducing the UHI effect, whereas the social value of community surfaced in the reasons given for the choice of the block typology. Its courtyard was perceived to provide spaces for the community and opportunities for neighbourhood interaction. Further values that were exhibited regarded a walkable neighbourhood, which resulted in the selection of less wide street profiles, as well as a green and liveable, but at the same time accessible neighbourhood, which was linked to the aim of achieving an economic, environmental, and functional balance between built up, street as well as open/green spaces resulting in the selection of streetscapes and block sizes of medium width and size.

In the future design of participatory exercises it will be important that the designer is aware of the values and preferences underlying and driving design decisions of laypeople and pays attention to these in their framing. Friedman et al. (2008) suggested to offer a range of indicators in interface design that clearly relate to and address the values of the user group. Our exercise lacked clearly identifiable indicators, which manifested itself in participants criticising the lack of information and explanations on the impact of the available parameters on the design. This affected the effectiveness with which participants could select a solution matching their design intentions and goals. The provision of relevant indicators, either as input parameter to guide the design space exploration process or as output parameters in form of design feedback and performance characteristics, will consequently allow laypersons to more effectively express and attain their goals.

Furthermore, the definition of clear and attainable participation and engagement objectives is important to ensure that the input provided by non-experts provides meaningful insights and value to the designer (Sanders, Brandt, and Binder 2010). However, it is important to note that the limitations of the medium of exchange employed act both on the designer as well as the end-user. From the designer's point of view, authoring a parametric model that can be efficiently translated into a web-based exploration framework, such as, in the case of this current study, the Beta.Speckle interface, imply sacrificing some of the initial fluidity and sophistication that the original authoring tool (Grasshopper) offers. Other frameworks, while offering a more flexible tool to the end-user, partially relinquish the precision, control, and evaluation methods that a parametric model offers. Similarly, from the point of view of an end-user, engaging with such a tool implies a potentially onerous task of understanding an abstract representation that the designer enabled, one that does not necessarily match a lay-person's expectations.

Consequently, one must not underestimate implications on the design process that such tools might have. Like with every other tool, digital or not, Beta.Speckle imposed certain limitations on the authors in how they could define the parametric model; similarly, it imposed a certain mental effort on the participants due to its available representation qualities. Furthermore, some constraints, such as the size of the solution space exploration, can be seen as having opposing values: for example, from the designer's point of view, a larger solution space is seen as a positive quality; conversely, for an end-user, a larger solution space may introduce further mental fatigue through the appearance of "choice paralysis" (Barry 2004). Nevertheless, given the current pace at which the underlying technology evolves, the trade-offs will, most probably, have a diminishing impact as the frameworks progress.

CONCLUSION

This paper described an approach for citizen engagement, which allows designers to share a parametric design space via the online interface and application Beta.Speckle with a lay-audience. The approach was tested and evaluated in a user study, in which participants were asked to select a preferred urban layout for a site in Tanjong Pagar. Participants could explore the given design space by varying building typology, density, streetscape and block size.

Analysis of the design exercise uncovered the preferences and values of participants and how these affected the choice of specific design variants. A preference for visual order resulted in the selection of visually simple, organised and balanced proposals, as well as proposals that provided visual consistency in relation to the surrounding context. Values of walkability resulted in a preference of narrower streetscapes, values of an accessible, green, sustainable and liveable urban neighbourhood in a balanced distribution of built-up, open, and street spaces with limited density. Economic considerations related to land scarcity led to the choice of high density layouts and the social value of community resulted in a preference for the block typology offering communal spaces. For the future design of exercises it was therefore concluded that the definition of indicators relating to citizens' values and preferences will allow for a more effective exploration of the design space and provide more meaningful results.

Although Beta.Speckle was considered easy to use, issues with the usability and usefulness were detected. Possible improvements relate to the presentation of the model, as well as the user interface and functionality of the tool. Nevertheless, the investigation has shown that the approach provides an interesting avenue to support the exchange between expert and laypeople in urban design. Future work in the area should include investigations into the impact of the approach on the expert design process.

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The Digital Twin

Tackling Urban Challenges with Models, Spatial Analysis and Numerical Simulations in Immersive Virtual Environments.

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For the built environment's transformation we are confronted with complex dynamics connected to economic, ecologic and demographic change (Czerkauer-Yamu et al., 2013; Yamu, 2014). In general, cities are complex systems being a ``heterogeneous mosaic'' of a variety of cultures and functions, characterised by diverging perceptions and interests (ibid). The juxtaposed perceptions and interests in relation to ongoing spatial processes of change create a particularly complex situation. Thus, for planning processes we are in need of approaches that are able to cope not only with the urban complexity but also allow for participatory processes to empower citizens. This paper presents the approach of using Digital Twins in virtual reality (VR) for civic engagement in urban planning, enriched with quantitative and qualitative empirical data as one promising approach to tackle not only the complexity of cities but also involve citizens in the planning process.

Keywords: *Digital Twin, Collaborative Planning, Planning and Decision Support, Participation, Virtual Reality, Global System Science*

INTRODUCTION

This approach enables citizens in a novel way through the use of digital emerging technologies. Until now, Digital Twins have been mainly used in the field of engineering and their implementation for towns have only recently been discussed (Batty, 2018). Digital Twins are digital representations of material or immaterial objects, such as machines, from the real world. They enable comprehensive data exchange and can contain models, simulations and algorithms describing their physical counterpart and its features and behaviour in the real world (Kuhn, 2017). To enhance a real life perception, Digital Twins can be implemented in Virtual Realities (VR). A Digital Twin is not an exact copy. This results from a classical dilemma in modelling, as models always have a certain level of abstraction and only represent physical reality with an error margin. A Digital Twin can be best characterised as a container for models, data, and simulation. The term "Digital Twin" has been coined and first used in relation to mechanical engineering, where they have already been applied for several years (Kuhn, 2017; Dembski et al., 2019).A criticism of Digital Twins is that they represent only a limited set of variables and processes and rarely include any of the processes that determine how a city works in terms of its social and economic functions (Batty, 2018). We therefore conclude the paper with a discussion of the presented results and further research direction how to include more social and economic functions using a synthetic population model (Dembski et al., 2019). Using a Digital Twin in VR not only is a novel way for collaborative planning processes, but also enables participants with different backgrounds to achieve an agreement. Digital Twins for towns will inform urban planners and designers in understanding impacts of intended urban change, also allowing citizens to have a voice and opportunity to influence public decisions for smart, sustainable cities already at an early stage (Dembski et al., 2019). The implementation of different analytical methods, as well as data and simulations for traffic and emissions, among others, is a great improvement for using the Digital Twin as an analytic and predictive tool.In general, digital technologies and their applications are of great importance for processes bridging formal and rational knowledge with informal and implicit knowledge. Our approach aims to support the creation of knowledge for smarter, more sustainable governance of urban regions involving the experience of citizens (civic science) supporting a democratic planning process. Consequently, this paper contributes to the debate of digital tools and their development with mixed methods for civic engagement and decision support in the field of urban planning. Our research involves 3D interactive simulations in virtual reality in combination with qualitative and quantitative data and methods such as space syntax. We present the development and test application of a Digital Twin in virtual reality for the 30,000-person town of Herrenberg, Germany. Our modelling approach includes a mixed method of 3D models, simulations, 3D mapping, and a street network model with space syntax. For citizen participation, the Digital Twin was embedded in the collaborative visualisation and simulation environment "COVISE." The Digital Twin for Herrenberg was exposed to approximately 1,000 citizens using both a mobile and stationary virtual reality environment (Dembski et al., 2019). For verification and consolidation, a survey was carried out. The results demonstrated that the use of this method and technology could significantly aid in participatory and collaborative processes (Ruddat, 2019).

In general, visualisation of complex processes and data related to participation of heterogeneous groups is essential. To that end, we developed a Digital Twin that can be applied and visualised seamlessly across all scales, on multiple layers, and in different categories of data in virtual and augmented realities for collaborative and participatory processes (PP), focusing on planning and decision support. For all participatory processes, we used collaborative VR environments. The advantage of using VR environments-such as stereoscopic back projection units, large 3D displays respectively tiled display systems or CAVEs (Cave Automatic Virtual Environment) -is that different participants with diverging professional and personal backgrounds can be informed simultaneously. These technologies can enhance discussion and help build consensus among stakeholders (Dembski et al., 2019). In this context, VR facilities, Digital Twins and visualisation techniques are highly useful: As Arnstein (1969) points out, it needs real power and not empty rituals to affect the outcome of such processes. Our approach described here allows not only citizens, but also decision makers and planning professionals to use the tools to achieve partnership: A Digital Twin offers great potential in the field of digital tools. Enriched with quantitative and qualitative empirical data, Digital Twins serve as one promising approach for tackling not only the complexity of cities, but also to involve citizens in the planning process (Dembski et al., 2019).

Beyond these applications, it has great potential to support option testing and scenario development for different planning fields and at all scales. Using a Digital Twin in VR is not only a novel way for collaborative planning processes, but also facilitates consensus building among participants with different backgrounds (Dembski et al., 2019). This is further connected to a common learning process linked to educational aspects such as involving youth or different other groups of citizens who are usually less involved in such processes. As Glaeser et al. (2006) rightly points out, better-educated citizens are more likely both to preserve and strengthen democracy.

PILOT APPLICATION OF THE DIGITAL TWIN: HERRENBERG, GERMANY

Herrenberg is a medieval town in south-western Germany with a population of approximately 30,000. The town encountered urban growth in particular during the industrialisation age and after World War II. The city belongs to the metropolitan region of Stuttgart with 5.2m inhabitants - a region characterised by fragmented peri-urban landscapes - a diffuse belt in-between urban agglomeration and rural landscapes characterised by multiple agglomerations, low population density (Dembski et al., 2019). This results in high dependency on infrastructure and increasing individual transport. Stuttgart's hinterland can be characterised in general by high levels of traffic, mainly reasoned in the high dependency on transport for commuting, fragmented communities and a lack of spatial governance (Ravetz et al., 2013).

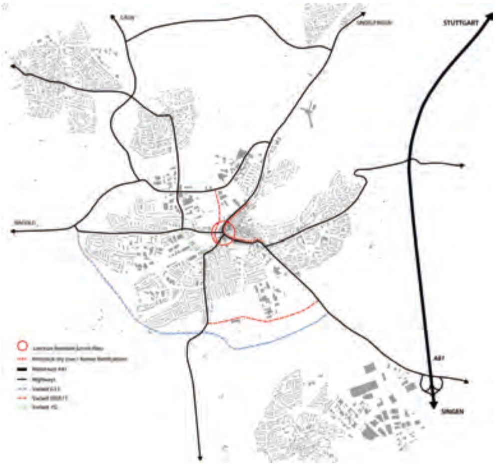

Figure 1
Figure-ground diagram of Herrenberg illustrating the high ranked street network and three traffic-planning scenarios. (Dembski, 2019)

Herrenberg consists of a homogeneous historic core; a fragmented urban fabric defines the urban fringe. The historic centre is highly affected by individual motorised traffic due to planning decisions and implementations in the past: A main road is leading the traffic directly through the historic core where it is merged with three highways. Thus, this area is exposed not only to high traffic volumes but also to environmental pollution by emissions and noise. In order to solve this urban challenge, the city of Herrenberg developed an integrated mobility plan (IMEP 2030), which shall serve as the guideline for the mobility development over the next 15 years. This process was supported by civic engagement. During the longstanding planning phase, nine different traffic scenarios have been developed until in May 2019 the implementation of one of the variants has been decided. We used IMEP 2030 and other urban planning projects as a test application for our Digital Twin to approach a novel way for enhancing collaborative planning processes.

METHODS AND DATA

Our research method is empirical and computational using a mixed method approach. In this research, we developed a Digital Twin and visualised it in VR for supporting participative and collaborative planning processes. The Digital Twin is set up as follows: (i) a morphological model (built environment); (ii) a street network model using the theory and method of space syntax; (iii) an urban mobility simulation with SUMO and wind flow simulation with ; (iv) qualitative and quantitative data using Volunteered Geographic Information (VGI) with a mobile application "Reallabor Tracker" developed for this purpose; and (v) a pollution simulation using an empirical data set from a sensor network (Dembski et al., 2019). For the Digital Twin, we used the collaborative visualisation and simulation environment 'COVISE', an extensible distributed software environment to integrate simulations, post processing and visualisation functionalities in a seamless manner. COVISE is designed for collaborative working, allowing users to collaborate through CSCW during the analysis of the Digital Twin or other data and models. COVISE supports projection based virtual environments such as CAVEs (Cave Automatic Virtual Environment), Powerwalls, tiled displays and domes but also a wide variety of HMDs (Head-Mounted Displays). Users can analyse their datasets intuitively in a fully immersive environment through state-of-the-art visualisation techniques such as direct volume rendering, high performance point cloud rendering and traditional surface rendering or ray casting (ibid). For the town of Herrenberg, Germany, we carried out a pilot-application.

The Digital Twin builds on a solid 3D city model based on a digital building model (i) provided by regional authorities (LGL), where additional detailed modelling was supplemented and 3D scans were integrated. While the model includes an overall level of abstraction, selected potential architectural projects with an expected impact on the neighbourhood and citywide level were represented in detail. The model was developed with a focus on the support of decision makers as well as for the use in participatory processes.

By using space syntax (ii) and the software depthmapX, we could analyse the potential through movement which refers to the movement passing the shortest routes from all points to all points in the road network (cf. Hillier, Burdett, Peponis, Penn, 1987).We analysed the status quo (2018) as well as nine different traffic-planning options, developed by traffic planners for reducing congestion in the city's core (Brenner, 2014). The results show different expected traffic development and build the basis for further application of methods.For the space syntax model, a hybrid model was chosen that combines road centre lines based on geographic information data and axial lines for areas with greater detail. Notably, emission data linked to airflow simulation were coupled with the NACH (angular segment analysis) mean value for neighbouring street segments in the length of 60m to 100m (Dembski et al., 2019). In the following step, the model was converted from two-dimensional to three-dimensional data for the visualisation in VR. In order to achieve three-dimensional space syntax visualisation, we developed new modules for COVISE and the OpenCOVER software. These novel features allow for an automated processing of two-dimensional geo-referenced space syntax data to be presented in three-dimensional virtual reality for collaborative platforms like the Cave Automatic Virtual Environment (CAVE) or other devices like 3D-Powerwalls or head mounted displays.

For a better understanding of traffic behaviour, we extended the model with a traffic simulation using the software SUMO (Kraizewicz, 2010) . This simulation uses a microscopic, space continuous and time discrete car-following model and lane-changing model. The results of the simulation are displayed in 3D as individual cars, trucks and buses driving through the 3D city model. A new plugin was developed to simulate and visualise changes in modal-split and amount of travel in real-time. This allows illustrating different scenarios and visions with the focus on traffic reduction.

Data, such as particulate matter, temperature, and humidity from the sensor network, was correlated with the space syntax model respectively its calculated values for route segments (potential through movement) and combined with traffic simulation and traffic counts (the latter provided by traffic engineers). For the integrated airflow simulation, official weather and climate data were integrated (prevailing wind direction and average wind velocity). This combination allows investigators to relate emissions to the potential volume of traffic and the distribution of emissions taking the wind and factors like temperature and humidity into account. This is also transferable to other emissions (simulation of NOx, CO2, etc.) and climate data (simulation of floods, urban heat, air lanes, for example) and is of course scalable to other sizes of cities and regions. The processing of required (big) data and the simulations can be calculated in real time supported by high-performance computing (HPC) (Dembski et al., 2019).

Volunteered geographic information (iv) can be accessed in different ways (Poplin, 2012). With

Figure 2
Space syntax NACH analysis of three traffic planning scenarios and the current situation in 2D. (Dembski, 2018)

the development of mobile devices such as smart phones and tablet computers, possibilities opened up novel ways of collecting geographic data: Information can be collected on site, directly where it was observed by the users, in this case, citizens (iv). Goodchild writes about citizens acting as sensors (Goodchild 2007) contributing data to GIS-based systems that are often free of charge, open source, and available as mobile applications for smartphones or other mobile technologies. He coined the term "Volunteered Geographic Information (VGI)." In a VGI environment, the user contributes his or her knowledge about the environment and is able, through user-friendly interfaces, to enter this data into the system, which stores it in a geographic database. VGI is compatible with GIS and can relate this geo-referenced data with other attributes, such as the characteristics of information, objects, or temporal and spatial information. The smartphone as hardware supports geo-referenced, photographic, and audio data, as well as comments written as text right on site. This data was implemented and visualised in the Digital Twin via a COVISE interface and tool in near real time. In order to collect empirical data through VGI, the mobile application "Reallabor Tracker" was developed (Dembski et al., 2019). The application allows users rate the quality of stay and readability of the cityscape based on urban elements in the thinking line of Lynch (1960) and registers their stationary activities and choice of transport. Furthermore, the ap-

Figure 3
Stereoscopic visualisation of the Digital Twin in the CAVE: a) Current situation / point clouds in scale 1:1, walking mode; b) space syntax NACH analysis linked to data of particulate matter and airflow analysis in big scale and flyby-mode; c) Overlay of space syntax analysis and movement patterns (VGI); d) Movement patterns combined with other VGI data collected with the mobile application. (Dembski, 2019)

plication registered spatially and chronologically differentiable movement patterns using traces created by GPS data. Open spaces were rated according to evoked emotions such as trouble spots or the spatial quality of paths or for stationary activities as well as urban barriers, etc. (Figure 4). Users had the possibility to take geo-referenced pictures, voice and/or urban soundscape recording and text notes from specific locations and situations. The empirical VGI data created by users of the mobile application ("Reallabor Tracker") were linked with the space syntax model and visualised for interactive use in virtual realities (Gudat, 2019).

Figure 4
Volunteered geographic information (movement traces, stationary activity, quality of public spaces) collected by young citizens using a mobile application: Georeferenced data in the Digital Twin, visualised in the CAVE (VR). (Dembski, 2019)

Because of well-known serious far-reaching effects on health, the air quality is monitored in most middle European cities. This usually occurs by networks of individual air quality measuring stations operated by state authorities. Because of high costs of hardware and maintenance, they offer only very low resolution for spatial measures (Dembski et al., 2019). The fact that emissions are not stationary but mobile, and that they are subject to a high level of spatial and temporal variability, there are questions about the capability of official sensor networks to gather adequate data of defined neighbourhoods and areas (Kraft, 2018). Alternatively, air quality can be determined via crowdsourcing. This term is used in earth sciences for the collection of environmental data by a potentially high number of people. Volunteers create geographic information (VGI) that usually is provided by states agencies or other official institutions (Goodchild, 2007).

Several civic engagement projects with the aim to collect emission data by using low-budget sensors already have emerged (Ling-Jyh et al., 2017). These projects usually rely on Wi-Fi or less common LoRaWAN (Long Range Wide Area Network) for data transmission. The sensors are collecting in most cases data on particulate matter, air temperature and humidity and are quite reliable. Occasional incorrect measurement of single stations is balanced with measurements of the other stations. Data is collected and stored on a server for almost real-time availability to be used in analysis, simulations and visualisations. We collected empirical data using a sensor network for temperature, humidity and particulate matter. This data was then correlated with a traffic simulation (Dembski et al., 2019).

COLLABORATIVE VISUALIZATION AND SIMULATION ENVIRONMENT

COVISE is an open-source modular visualisation system, designed to support collaborative visualisation of data in virtual environments as well as on the desktop. The architecture of COVISE allows developers to extend the existing functionality by integrating new code as modules. In a visual application builder, these modules are connected to form a dataflow network (Figure 5).

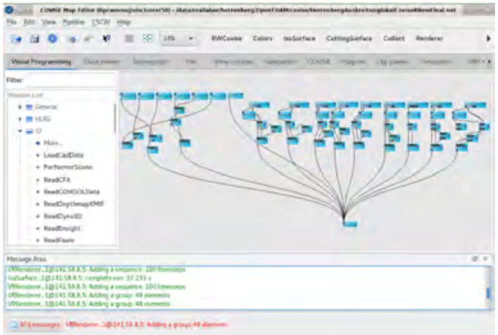

Figure 5
The COVISE desktop user interface: Visualisation pipeline of the "Herrenberg" dataset. (Wössner, 2019)

At the end of the pipeline there is a render module, which can either be a desktop renderer, or the VR- oriented render module, OpenCOVER. The pollution simulation was carried out in OpenFOAM. COVISE already provides a read module to read in results from parallel unsteady OpenFOAM simulations and existing modules can be used to visualise geometry, cutting surfaces, isosurfaces, streamlines, etc. New modules have been introduced to read depthmapXnet data, project georeferenced data and drape 2D data to 3D elevation maps. All this data is then rendered in OpenCOVER together with the 3D city model. OpenCOVER is based on OpenSceneGraph and supports any type of projection- based VR environment such as CAVEs, powerwalls, domes, or tiled displays. It further supports VR and AR Head Mounted Displays. C++ plugins can be developed to extend the functionality of OpenCOVER. A number of plugins have been developed or extended to visualise the data for this research. Large-scale terrains are rendered through Virtual Planet Builder (VPB) or osgEarth. VPB had to be extended to align the uneven terrain to high-resolution streets represented in the OpenDRIVE format in order to prevent visual artefacts. Point clouds from terrestrial LIDAR scans (light detection and ranging) have been sorted into an octree data structure for efficient rendering. 3D city models can be loaded in various data formats: CityGML and DXF in case of the pilot-application Herrenberg.

OpenCOVER not only provides 3D navigation in the virtual model but also allows for interaction with the visualisation modules thus cutting surfaces and streamlines can be interactively placed anywhere within the city to analyse the airflow. Colour maps or the size of tubes representing space syntax, for example, results can be visually and graphically adjusted to one's liking.

COLLABORATIVE PLANNING AND PUBLIC PARTICIPATION

The use of a Digital Twin based on VGI and crowdsourcing for civic science fits well into Arnstein's ladder of citizens' participation: It enhances low-threshold access to information, participation in data acquisition and ensures a broad understanding of complex topics related to urban planning. Arnstein (1969) points out, that power is in fact redistributed through negotiation between citizens and powerholders (rung 6 of the ladder). A tool like the Digital Twin enables citizens to engage in trade-offs as strong partners (Dembski et al. 2019).

For the participatory process we used stationary (Figure 7) as well as mobile virtual reality environments (Figure 6). The mobile version consists of a powerful computer, a mobile back-projection wall, a 3D projector including optical tracking equipment and a Vive Pro Head Mounted Display. The stationary virtual environment we used was a five-sided CAVE

(Cave Automatic Virtual Environment) at the High-Performance Computing Center Stuttgart. Participants could experience the interactive model in collaborative VR environments in groups of 10, in a time frame from 10 to 15 minutes. For both, the mobile and the stationary VR environment active stereo shutter glasses and an optical tracking system for navigation were used for interaction and correct representation of the perspective for the viewers. More than 700 people of different age and backgrounds in particular children and adolescents took part in multiple participatory processes "on site." Furthermore, with the help of VR, we could involve citizens with migration and different language background, groups of elderly people and even deaf and otherwise challenged participants. All of these are marginalised groups that are commonly not included into urban planning citizen participation (Dembski et al., 2019).

Figure 6
A mobile immersive VR during a participatory process with participants of various age with different backgrounds in Herrenberg (on-site). (Dembski, 2019)

In addition, we offered participatory workshops in the CAVE, by its nature a stationary virtual reality environment situated at HLRS. This was the option mainly used for planning professionals, decision makers and youth organisations. In total, approximately 300 participated using the stationary VR environment and approximately 700 participants using the mobile VR (ibid).

A questionnaire was developed with the support of a sociologist and we gathered 40 responses with an age range of 16-80. The respondents had diverse professional and educational backgrounds, from students, educators and police officers to IT experts and decision makers.

The questionnaire consisted of 9 questions focussing on quantitative queries about the perception of the visualisation in form of a polarity profile as well as open questions relating to the perceived use and potentially missing information. This enabled us to collect both quantitative and qualitative data. Based on this survey, we wanted to find out about the users' acceptance regarding the Digital Twin and virtual reality versus conventional instruments used for participatory processes (Dembski et al., 2019).

The results showed that all in all, the experience in the VR environment was received very positively: The Digital Twin, specifically its representation in VR, was perceived as very beneficial and interesting. Visual evidence was also very well regarded. For the participants it was equally understandable, clear and entertaining. Users were also asked about the benefits of virtual urban models in the context of public participation processes respectively municipal planning processes. In both cases the answer was clear: Almost all participants agreed on the usefulness of such tools. "The situation can be experienced from all perspectives," "It provides a better understanding concerning consequences and implications," "Easily understandable - everybody can understand planning better that way," were just some of the comments given by the participants (Ruddat, 2019; Dembski et al., 2019).

Clarity and transparency are seen as major advantages. These user expectations are important when it comes to interaction between administrations, different experts and citizens and, in this context, for communicating urban planning and design topics simply and comprehensibly. A Digital Twin as built up in our case study is certainly suitable to convey complex information from administration and planning professionals to citizens and, vice versa, to include citizens in urban planning and design processes in the sense of civic engagement and citizen science (Dembski et al., 2019).

Figure 7
A group of young citizens using the CAVE during a participatory process at the High-Performance Computing Center Stuttgart. (Dembski, 2018)

CONCLUSIONS

In this paper we set out to present the development of a Digital Twin involving different models, methods, analysis and simulation. It summarises our development of a Digital Twin, a novel tool in the field of urban planning. We used a variety of techniques and methods such as 3D modelling, urban mobility simulation, wind flow simulation, space syntax, people's movement patterns, stationary activity data and qualitative data to configure the Digital Twin. For our pilot application we chose the 30,000-person town of Herrenberg, Germany-an urban area in the peri-urban region of Stuttgart that contains high traffic volume and pollution. This gave us the opportunity to test a series of scenarios and potential solutions as well as evaluate their impacts using a real-life case. It serves as our first European application for a Digital Twin for urban planning and design. The Digital Twin allowed us to gain a better understanding of potential solutions for urban challenges involving public decision-making to reach consensus.

For consolidation and validation of the Digital Twin we carried out a questionnaire with 40 participants which will enable us to not only evaluate the meaningfulness of our approach, but also to adjust the Digital Twin to the needs of citizens in order to provide with an easily understandable model for the complexity of the built environment.

By its nature of a model and therefore an abstraction of reality, a Digital Twin does not include all real-life information. It is an objective to achieve similarities to the real world and a level of detail accurate enough for concrete (but complex) problems. Furthermore, Batty (2018) states that there remains a strong need for additional social, economic and environmental data.

Consequently, we are continuing our research in the context of Global System Science (GSS) related to these areas. Therefore, we are currently working on an integrative toolbox for global systems analysis. The integration will be centred on recent methodological advances in the construction and use of synthetic populations. These synthetic populations provide models of given populations, typically of humans, but also of cars, buildings and more. A synthetic population is based on individuals that are different from the actual ones, but in such a way that the population as a whole matches the empirical one in the distribution of attributes and relations that matter for the problem at hand. In our current research, we aim to provide generators for such populations at a global (worldwide) scale while also at smaller scales. The case study of the Digital Twin described here forms just one piece in the big puzzle (Dembski et al., 2019).

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Caronae

ridesharing and first steps into commuting opportunitie of academic exchange

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Location-based mobile applications have been a rising theme for academics in the field of urbanism and in urban and transportation, because of the potential of transformation they might bring to the urban landscape (De Souza e Silva, 2013). One of the possibilities we study here is to observe social encounters fostered by commuting rides. In this paper, we try to examine the practice from the broad perspective of estimating the environmental benefits, in a context where digital information technology is wielded to address problems old and new (Townsend, 2014). This paper aims to analyze the potential of transformations that new ICTs bring to urban mobility, using as case study the official ridesharing system of the Federal University of Rio de Janeiro, the Caronaê project. The system was developed focusing on the reduction of the number of motorized trips to the University, as well as the amount of CO2 generated by them. Here we analyze the dynamics of ridesharing, using the system data, and also try to observe the role it may play towards the promotion of integration in the UFRJ community.

Keywords: *mobile apps, urban mobility, ridesharing, caronae ufrj*

INTRODUCTION

Urban mobility is a central issue for big cities today. Everywhere the impacts of urban planning directed at the private owned cars is felt, and even harder in places such as Brazil with relatively small investment in public transportation. The results accumulated throughout the years have directly influenced the quality of life of citizens in urban centers. More frequent - and lengthier - traffic congestions have altered daily commuting travel times. This, and an increase in the number of car accidents and air pollution rates, adds up to elevate daily stress in urban settings. In Rio, as well as in other metropolis around the world, collective transportation is ill-planned and frequently inefficient, with little intermodal connection, limited routes and overcrowded at peak times. Most cars used to commute travel as single-occupant vehicles, generating externalities like congestion and pollution. A relatively efficient and sustainable transportation option for addressing these concerns is ridesharing-the practice of sharing a car with other passengers, either for free or by sharing travel expenses.

Information technology has long been used to help urban mobility, and the recent developments in GPS and mobile technologies has been rapidly adopted, and fostered a whole ecology of urban mobility applications. Indeed, it can be argued that terms like "smart cities" are heavily connected to urban mobility solutions, and that they are among the first types of applications people think about when referring to such terms. Apart from mobility in itself - hailing a cab, informing where is and when will arrive the next bus, for instance -, many applications that use geo-referenced information, such as taxi apps, Uber, public transport monitoring applications, bicycle and car sharing applications, generate a plethora of data on urban dynamics. Most of the time, this data is used to further improve urban transportation systems, working as a feedback system. However, there are many social and cultural patterns embedded in such data that can be used to interpret and describe many urban phenomena. One of the first and most widely known examples is "Real Time Rome", teh MIT Media Lab project developed as part of the 10th International Architecture Exhibition in Venice to visualize different location and movement patterns of cellphone users in the Italian capital city, identifying which monuments concentrated most tourists, for instance (Calabrese and Ratti, 2006; Calabrese et al, 2011). In Spain, Borge-Holthoefer et al (2011) analyzed popularity and social network distribution of tweets about the protests in May 15th of the same year. Another example is how Netto et al (2018) use Twitter locational metadata and demographic data to potential encounters occurring among people of different economic status in Rio de Janeiro.

This paper aims to present the analysis of current data from the official ridesharing application of the Federal University of Rio de Janeiro. The research goal is to identify whether ridesharing does provide opportunities of academic exchange inside the University, among different courses and among different groups of people. In the process, we also try to observe the larger picture of ridesharing behaviour in our University, as well as indicate possible further developments of the ridesharing system itself, especially in its administrative interface.

The first part of the paper presents the Caronae project, since its creation to operation and future developments. The project intends to safely connect people who attend the campus of the University and have the same daily routes, based on a mobile application and designated meeting points throughout the campi. We analyze the different aspects of the project, within a theoretical framework about the use and possibilities of the new ICT and location-based technologies for the cities, to understand its insertion in the urban context.

The second part of the paper compares Caronaê to similar apps, examining how each app deals with urban mobility in general. We address a previous stage of the research that presents the classification of examples of digital platforms in four main categories according to the type of function they carry out on urban mobility. This allows us to recognize the context in which the project to be analyzed is inserted

In the third part, the Caronaê database is examined, in order to find its demographics and to identify possible patterns, especially concerning diversity chance encounters of its users. First, we focused on the dynamics of urban mobility and the effects of ride sharing on the university's round trips, that is, how it helps to mitigate the effects of private car oriented transportation. As a complementary analysis, we also sought to reflect on how the system creates networks of interactions among users, strengthening community ties among the institution and promoting a greater exchange between different profiles of users and categories of UFRJ.

CARONAÊ: A RIDESHARING SYSTEM AT UFRJ

The Caronaê UFRJ project is the official ridesharing system of the Federal University of Rio de Janeiro. The system consists of a mobile application restricted to the academic community (students, professors and administrative technicians) combined with sig-

Figure 1
physical displays of official meeting points inside the University

naled ridesharing meeting points near the buildings of different UFRJ campi. The system allows the sharing of car trips, optimizing the daily commuting to the University.

Concept

Initially, the idea of Caronaê came from a group of UFRJ students, as a proposal for the “Sustainable Solutions” competition organized by the UFRJ “Green Fund” in August 2014. The project was awarded in the category “Mobility” and began to be implemented in 2015.

The Caronaê system seeks to securely connect people who attend the campi of the Federal University of Rio de Janeiro and carry out daily commutes in common. It started with the main campus, at Ilha do Governador, where access has always been an issue, due to scarce options of collective mass transportation - nowadays, only regular buses and BRT vehicles; there is no access by subway or train, or even maritime access (since it is an island). Therefore, many people opt for the use of private cars, which creates enormous problems of traffic, especially at peak times. Also those private cars usually transport only their drivers, an occupancy rate below that supported by the vehicle. If historically ridesharing has always been an option, to offer a ride to (or accept one from) strangers is a practice that has noticeably diminished over the years, mainly due to safety issues.

In this sense, the project identified a constant and growing demand of the UFRJ community and sought, through the resources and options offered by the technology, to unify all car offers in a single platform, aiming to facilitate and expand the ridesharing dynamics, while somewhat ensuring that participants were verified members of the UFRJ community, thus potentially improving the safety of the practice.

The name Caronaê derives from a contraction of the Brazilian word “carona”, that means ride, and the interjection “aê”, characteristic of the way of speaking in Rio de Janeiro, indicating an appeal or call, and its initial inspiration came from the use of the expression “Vai uma carona aê? ”, that means “Do you want a ride?”.

Implementation

Since its idealization, the project has been divided into three parts: the virtual framework, consisting of the software and the underlying database; the physical framework, consisting of the physical displays of official meeting points inside the University; and the cultural framework, based on the constant need to advertise the system and its benefits to its potential users, in order to expand among older students, teachers and other servants, as well as to attract the new users that enter the University each semester.

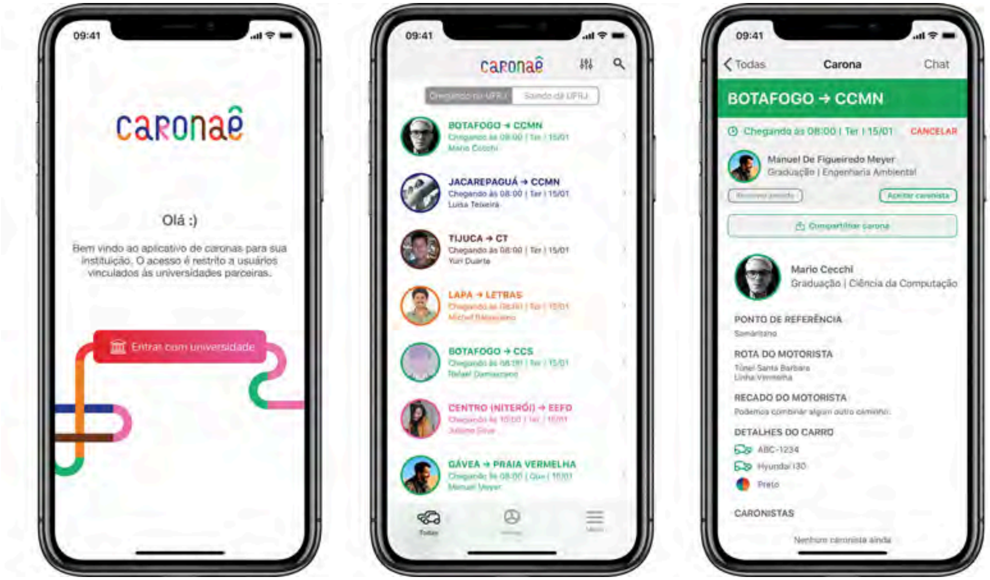
Figure 2
Caronaê’s official website

The virtual scope is the basis of the system, consisting of a mobile application for Android and iOS systems, which concentrates the offers of rides and the database that lists the system information on the server. The system basically functions as a digital platform where each driver can offer the rides, and other users can request them while browsing through a list of offered rides. Users who wish to offer rides can publish them by informing the following information: 1) If it is arriving (inbound) or leaving (outbound) UFRJ ; 2) Origin; 3) Reference point; 4) Route; 5) Destination; 6) Date and time; 7) Spots available It is also possible to inform whether a ride is routinely offered on a weekly basis or if it is a single offer, and to include additional notes like: “no smoking and no pets” or “contribution of 4,00 reais” .

Offered rides are available to all users in the “All” tab of the application, which provides filters by zone, neighborhood and campi. The process of searching and requesting a ride is done by accessing this list. When finding a ride, the user can choose it, see more details and, if he or she wishes, make the request to share the trip. The driver who offered the ride receives the request and can evaluate whether or not he accepts, accessing more information on the profile of the rider. If the evaluation is positive, the driver accepts the request and the rider receives a warning. From there the two users are connected through a private chat within the app and some additional information about the ride is made available, such as: model, car plate and the contact information of all participants. In the “My trips” tab, all the offered, pending and active rides of a user are also related. Drivers, in addition, can see their past and pending offers. Rides can be “pending”, that is, with requests waiting to be accepted, or “active”, with at least one accepted request.

Taking into account the safety of the users, the Caronaê is based on the premise of an access system exclusive for the community of the University, a differential that guarantees greater safety for users and hitchhiking practitioners. In order to realize this premise and ensure that only active members of the University (student, professor or technical-administrative) have access to the service, the system connects to the UFRJ registration database, through the support of the Information and Communication Technology team (ICT-UFRJ). Access to the application is through the CPF number and the UFRJ Intranet password. This procedure guarantees the authentication of the user’s profile at the first access and associating some official data with the user profile that cannot be changed: name, category UFRJ and, in case of students, the course in which they are enrolled.

Figure 3
Screenshots of the Caronaê app



Use of the system

The system was launched in April 2016 and since then about 16 thousand users have registered and more than 50,000 rides were created. All the interactions performed within the system, since it is being active, are recorded in the database, as we will see in the third section.

Despite the difficulties along the way, the project had the support of the University campus manager after its implementation and in January 2017 was accepted as an official Extension Project, consolidating its institutionalization. The extension project is based on the expansion, through the replication of the system in other institutions, especially other public universities and is directly connected to the NIDES (Interdisciplinary Center for Social Development). This process was thought to be carried out by opening the system source code, that is, transforming it into an open source system, allowing its replication in other interested institutions in a much simpler and more collaborative way . From this model it was intended to create a connected network of contributions to the same source code, initially based at UFRJ.

Thus, in the middle of 2017, Caronaê was made available as an organization in the open source GitHub platform, following the GNU General Public License v3.0, which allows the total reproduction of the system, including for commercial and lucrative purposes, as long as the same is kept open, allowing any enhancements and new functionality to be added back to the original code. With the open source code the entire community is free to run, study, examine and track Caronaê's source code. All these modifications can be submitted to the project repository so that the changes, after being evaluated and incorporated by the team, are made available to all users of the Caronaê network.

It should be noted that data shows that the use of the platform has been decreasing over time, which the Caronaê team attributes to a few factors: technical problems at the beginning of the project; the lack of appropriate institutional support (funding, people and even the unclear institutional insertion of the project); the lack of continuous advertisement focused on new students; and the competition with other platforms, both specialist and non-specialist. Most of the rides in the dataset were recorded from April, 2016 to December, 2016, with a minor resurgence from March, 2017 to May, 2017.

PLATFORMS FOR URBAN MOBILITY

Caronaê is only one of the many alternatives that seek to improve urban mobility through information technology. Mobility in the context of this article means the physical displacement in the urban environment. Amar (2016, p. 13) states that information has become an essential component of transportation systems, and mobile technologies only enhance this role (Townsend, 2014, pos. 17). Indeed, it can be argued that the whole concept of "smart cities" (and, in a lesser measure, its more critical counterpart, "smart urbanism") arises from mobility-related applications in its early days, and its development is greatly enhanced by the ubiquity of cellphones and their embedded GPS capabilities.

There is a wide range of mobility services offered or improved by mobile apps. In a previous work (Teixeira and Paraizo, 2018), we examined different apps for iOS and Android devices in order to understand how each one dealt with urban mobility and how they could be grouped. based upon some categories, such as ownership of the vehicle, multi or single modality, and if there is (and how it is done when present) sharing of costs and rides, in order to understand the benefits of each platform in terms of environmental and social issues. The idea was to contextualize the project in relation to other digital platforms for transportation and to understand some of the ways that they could affect urban mobility, whether they could help induce a more sustainable urban development and also how could they affect social networks and encounters.

We perceived four main categories (each one with their own subdivisions): 1) mobility orientation, that is, apps that help users to navigate around the urban environment, such as Google Maps, Waze and the French RATP platform, which can be uni or multimodal; 2) on-demand transportation, or e-hailing, such as Uber, Lyft and 99, that essentially provide taxi or taxi-like services managed by a computer server; 3) vehicle sharing, that provides a digital interface to rent vehicles usually for daily, short trips, such as Velib and BikeRio, for bicycles, and AutoLib and Car2Go, for cars; and finally 4) ride sharing, the category where Caronaê is included, as well as BlaBlaCar and Zimride, which deals with the offer of empty spots in a vehicle for a given trip, improving the occupancy of the vehicle.

This last category is especially important by number of reasons when considering both sustainability and the possibility of exchanges. First, improving ride sharing, digitally or not, works towards the rationalization of vehicle use, according to the concept of Mobility Management (Balassiano et al., 2005), which is pivotal in the case of cars: studies show that the mean occupancy rate of private cars traveling in Brazilian urban environments is around 1,4 (Cet-SP, 2011). This translates in relatively big vehicles occupying large chunks of streets (and ultimately public space) to transport a single person most of the time. If the other person - or persons - in the vehicle are also car owners, this means one or more cars are left out of the equation for that trip, which also helps reduce fuel use and carbon emissions. In fact, in a previous work (Teixeira et al., 2018, p. 300), it has been established that this happened 908 times since the system was online, and an estimated saving in CO2 emissions of about 2982 kg.

E-hailing (as regular taxi services), on the other hand, although works with improved occupancy rates, is indeed mostly transporting a single person, as the driver will still be riding the vehicle after the trip. Sharing a ride, however, also means that more than one person is going to be in the same closed environment for a few minutes, or even an hour, increasing chances of conversation among riders - as many than one taxi user can attest. It is very likely that ride sharing services that provide users with a common background, as is the case of Caronaê, will very likely induce conversations departing from this background. Also, as Caronaê deals with a daily commute of a closed (all participants know they belong to the same institution), large and relatively heterogeneous public (comparing, for instance, with an office building), the social exchanges may play an interesting role in spreading academic ideas and randomly connecting people. Even if in this stage of research it is not possible to confirm the actual social exchange, the examination of the database should provide some preliminary indication of how it could be happening.

THE CARONAÊ DATABASE

In this section, we examine Caronaê's database of rides and users in order to understand the profile of those involved, the distribution of rides along time and space and what kind of social encounters the system favors. As a digital platform, Caronaê has a database where all the information and system interactions are registered. We observe the data generated by the activity of the system to understand the dynamics of the rides in the UFRJ context, their space-time distribution and the social profile of the users, looking at it from both a broader perspective of environmental and climatic issues, highlighting how rides can be an alternative to reduce the number of trips in private cars - or make them more efficient - and from a more specific perspective of possibly fostering the encounters and exchanges inside an academic community.

The Caronaê database is an object-relational database, accessed by PostgreSQL, an open-source object-relational database management system. The queries are done through the SQL, Structured Query Language, extracting various information from crossing database records. The majority of analysis here presented was performed by exporting SQL results in CSV files and importing then into Excel for processing.

We can separate the information obtained from the Caronaê dataset into two basic categories: users and rides. The main data about the users comes from the app login process using the UFRJ login info. As explained in the first section, this authentication, in addition to ensuring that the user is an active member of the academic community, also links some user profile data, which cannot be altered by the user in the app, in order to guarantee the authenticity of the profiles and, consequently, raising the security of system users. It consists of name, category UFRJ, and course (in case of a student user). Other information is provided by the user to complete the registration in the application: email, contact phone and neighborhood of origin. If the user is a driver, he must also inform some car data: model, license plate and color. This information only appears for the users who are in the same ride, to facilitate the contact and the meeting of all the participants.

The records of rides consist of the following fields: direction of the trip (outbound or inbound UFRJ) , origin, destination, date, time, number of places, reference point and route. Working with the logic of the trip generating center (Redpgv, 2010), the Caronaê works for commutes related to a certain institution, in this case the UFRJ. That way, we have that, in inbound travel, the destination is always a hub of a UFRJ campus and the origin is always a neighborhood in one of the metropolitan area's regions. On the outbound or return trips the destination is one of the system designated areas in Rio.

User profile

As of the end of 2018, Caronaê had a total of 17,561 users. Of these users, 13,888 effectively completed the registration. Users who completed the registration are those who, after accessing and authenticating the profile via the Intranet, completed the additional contact information and added car information (when they want to register as trip offering drivers). For this study, we consider as active users in the system only the users with complete registration.

When analyzing the active users in the researched period, 94% of them are undergraduate or graduate students, divided into 9945 undergraduate users, 929 master courses students, 90 professional master courses students , 671 doctorate students and 55 specialization courses students. The total number of public servants, or University employees (teachers + administrative & technical staff) is 677, only 6% of total active users - data extracted from the UFRJ 2020 Master Plan shows that they are actually 20% of the academic community. Despite the large number of complete registrations in the system, the number of registered users who completed at least one ride is much lower, indicating that not all users have actually used the application.

In a ride, users of the system are classified as riders or drivers. From the system point of view, every user is potentially a rider, able to browse rides and request ride offers; to be a driver, the user need to inform their willingness to offer rides and register their car information , as well as actively offer rides. Considering an optimal use of the system, with a good amount of rides offer, a driver may choose to take a ride instead of driving, leaving the car at home. In 2018, 3094 users were drivers, which represents 22% of total users with full registration. Among drivers, student users represent a total of approximately 90%, leaving University employees as 10% of the total, a significant increase in relative participation in the system, although still less than the total number in the University. It is worth noticing that while the general car ownership ratio among students is around 1/5, it increases to 1/3 among students enrolled in Master courses.

The geographical distribution of the users by the city can be analyzed through the neighborhood that the user registers in its first registry. This data tells us about the main origin / destination of users, not actual rides. No matter how much the user offers rides coming from or going to points of the city others than the one informed in the user profile, the system so far is designed to record only that information. As it is, however, data still show us the general distribution of users across the territory. It allows us to know, for example, the neighborhoods with the most registered users: Tijuca, with 944, followed by Copacabana (590) and Niterói/Central Area (529) - Niteroi is a nearby city with a strong commuting relationship with Rio de Janeiro.

This geographical analysis of users in the city can also be made in relation to the rides registered in the system, revealing spatial aspects of the rideshare dynamics. The next section analyzes this and other aspects of this dynamic, seeking to better understand the impacts of the project on the urban mobility of the campus and the city in general.

Space-time distribution of rides

Since the system does not provide integrated mapping tools, geographic analysis is based on the selection of listed regions and text fields indicating the actual places people want to go, which makes it harder to process with accuracy. Regarding the data on rides, the major set of offered rides comprises a subset of concluded rides. A concluded ride is an offered ride that received at least one positive request and that request was accepted by the driver. Therefore, every completed ride is also an offered ride, but not every ride offered is necessarily completed. To date, more than 50,000 rides have been offered and 5,700 were completed, which makes for a rate of completion of approximately 12.5%. Most of the analysis shown here will take into account only concluded rides.

As stated before, the platform indicates locations in Rio de Janeiro by neighbourhood names only (although more specific locative information can be added to the “notes” field of each ride), and cities names when dealing with the metropolitan area. To facilitate browsing the rides offered, neighbours and metropolitan area cities are grouped into zones, based on the division of the UFRJ 2020 Master Plan (“UFRJ 2020 Master Plan”, 2011, p.34), which in its turn uses the official division of zones made by the administration of the city of Rio de Janeiro: North Zone, South Zone, Central Zone, West Zone, “Baixada” and “Niterói”.

Regarding the distribution of ride offers in the areas of the city of Rio de Janeiro, the North Zone is

Figure 4
Offered rides by city zone

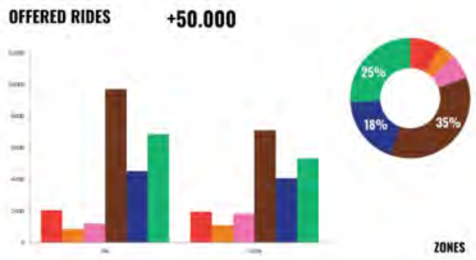


Figure 5
Completed rides by city zone

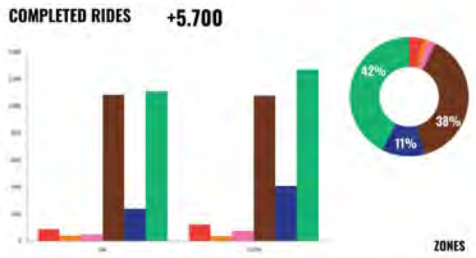


Figure 6
Offered rides by university building

Figure 7
Completed rides by university building

by far the one with the highest number of rides offered, totaling 16,778, of which 9,690 are inbound and 7,088 are outbound. The South Zone comes next, with 12,149 rides offered in total, of which 6,844 are headed towards the University and 5,305 leaving it. This corresponds to the daily travel research presented in the Master Plan for the main campus, where the North Zone appears as the largest destination, followed by the South Zone. However, when it comes to the conclusion rate, the South Zone is the area of the city that has the largest number of completed rides, 1107 inbound and 1229 outbound, 220 more than the North Zone, representing 19.5% of the rides against the 12.8% that account for the North Zone. So, the North Zone has the largest number of users and the highest number of rides offered, however, the South Zone has more rides effectively completed. In the number of rides offered, South Zone and West Zone are close, as in the number of users, but the conclusion rate is significantly lower for the West Zone.

In figures 4 and 5 we have the percentage distribution between the offered and completed rides, by city zones and university centers, also discriminated by inbound and outbound trips. It is interesting to note that the number of inbound trips is higher than outbound ones; but the number of completed rides tends to be approximately the same inbound or outbound, making outbound offers more likely to be completed for most of the city. This could be explained by the ease of organization of car rides within a relatively small area (when comparing to entire neighbourhoods) which is reinforced by the presence of the physical meeting points.

We can also observe the distribution for the different buildings of the campi Cidade Universitária and Praia Vermelha (figures 6, 7). The Technology Center (CT, home of Engineering Schools) is the the one that has more offered rides in and out, respectively 1,778 and 2,255, also has the highest rate of conclusion, approximately 15.4% in the trip and 21% in the way back. Praia Vermelha, on the other hand, has fewer rides offered compared to CT, but has a high rate of conclusion when outbound, reaching

15.7%. As before, the total number of rides offered is higher when inbound, but when outbound the rate of conclusion is higher, perhaps because when inbound, drivers have more time to offer the ride in advance than when outbound, when it may be more difficult to predict the exact time of departure from the University.

The weekly distribution points out that the day of the week with the largest number of completed rides is Tuesday. Almost every day of the week has a greater number of outbound rides completed than inbound, with the exception of Friday and Saturday (but on Saturday only a few rides happened). Daily times of rides indicate an increase during peak traffic times in the city.

As for the number of riders (not including drivers) in each ride, more than half (3646) of the total number of completed rides (5930) has only one rider, and approximately 25% (1506) of rides happened with two riders; about 10% of the rides (618) had three riders; full rides, comprising four riders, represent only 2.7% of the total. This indicates that it is important to foster the increase of car occupation, to have more efficient trips. According to the project data, the average car occupancy rate is 2.53 inbound and 2.56 outbound. Compared to the average occupancy rate of cars in large Brazilian cities, the Caronaê system provides a significant increase of this rate, rationalizing the use of private cars.

Network interactions: academic exchange in the UFRJ community

In addition to the effects on urban mobility, rideshares promote meetings. In the specific case of Caronaê, usually the trip to the University campus takes at least 20 minutes, this means that for 20 minutes the participants of a ride will be together in a car. And participants usually have a common origin and destination, that is, they either live or perform some daily activity in the same region.

The networks arising from the rides registered in Caronaê were therefore analyzed by combining users and rides data tables. This made possible to answer some questions regarding the reiteration of users in the same rides : we started with how many times the same users were together in a ride, that is, how many trips had the same participants.

It was necessary to resort to SQL and Python programming to combine the main tables (users and rides), and the very design of a data structure for the intended Excel manipulation proved challenging, let alone programming the data transformation in Python. It is worth mentioning that this process was carried out jointly by the Caronaê team. Still, most of the analysis we wanted to do were not viable using regular spreadsheets, which lead to a query code (that took four hours to run) that resulted in the following results: in 3229 times, the same two users were together on a trip (which does not mean that they were the only participants in that trip). We used similar queries for times when three, four and five people were on the same trip, resulting respectively in 438, 64 and 4 times. A curious outlier is the case of a full ride, with the same five people, that happened four times, which may indicate that the system might improve the formation of bonds through commuting after all, and lead to further investigation with other methods to support this initial findings.

Other questions arose, such as: how many trips had users of the same course?; or how many trips had travel with users of the same category in the University? And what those numbers represent in terms of the total number of rides? Further research will seek to improve the data extraction processes and the statistical tools in order to help us refine our questions and our answers. Are riders wanting more prone to take rides from the same course, or from the same category, or they tend to mix? Perhaps this is more common on the way back home, when people are concentrated in their respective buildings and, when inbound, it is more common that people are grouped by neighborhoods. Therefore, it is also important to know the number of trips with users with the same neighborhood of origin, revealing for example when people from close neighborhoods take rides, perhaps preferring to take a bus outside the campus instead of waiting more time for the right one there.

CONCLUSION

This paper brings a contribution to the discussion of the role of the location-based technologies and mobile devices in new - or renewed - possibilities for urban mobility. It also addresses a more specific concern with increasing opportunities of random creative exchange within a given community - one that congregates different skills but with a high degree of education. The paper is based on the assumption that those random encounters - in this case, while sharing rides - are part of a successful creative and innovative environment. We therefore study the dynamics of digitally mediated shared commuting in order to observe how different social and academic profiles mix are currently mixing - in contrast with other systems, even digitally mediated, where personal acquaintance - which tends to bring together those who think alike - is required.

Much is currently being discussed about the social implications of the massive use of information and communication technologies and of localization devices, especially regarding privacy issues, surveillance and population control. This is one of the keys to look at the subject, certainly a fundamental one. However, we argue here that we can also analyze - without losing sight of the critical aspects - other social dynamics that are mediated by mobile info-communication devices and localization technologies, from the perspective of the potential of the expansion and diversification of encounters, in the case of Caronaê, those occurring during shared rides.

Even if at this point it is not possible to confirm if this actually happens, it is still important to analyze the Caronaê database in terms of demographics, riding habits and possible indications of groups mixing. The results show that further research in this direction, employing surveys and interviews, for instance, could prove fruitful,as well as the aforementioned refinement of data extraction and statistical analysis tools. On the other hand, the database itself could be improved if the University could made available a few more data about the users. One of the most striking examples is gender, which could help determine whether women give preference to female drivers and rides. Or date of entrance in the University, that could help visualize adoption and abandon of the system along time. But the Caraonaê database itself has room for improvement: even if it does not include real time location of users during rides, for instance, it could improve records of origin/destination of each ride, instead of recording only the information connected to the user profile. Caronaê, and the research involving it, also has to deal with socio-cultural issues of adopting the specific platform vis-a-vis other common mobile apps such as Whatsapp of Facebook Messenger (which by their own nature cannot record accurate data about the rides), or more general ridesharing systems such as Wunder.

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Parametric Urban Design from Concept to Practice

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Little research has been made into the application of parametric urban design approaches to urban design in practice. On the part of urban design practitioners, lack of knowledge of parametric design, time constraints and a focus on day-to-day operations contribute to this situation. And on the part of parametric design researchers, lack of understanding of practice workflows, project types and media output types also contribute. The limited interaction between academia and practice in itself constitutes a barrier to changing the situation. This paper presents some first results from a research project aiming to overcome this barrier. The research design involves a theoretical framework for parameterising site design on the level of site layout, building forms and facade schemas. It also involves an analysis of typical workflows from urban design practice, as well as of the types of media which are typically used to present urban design projects.

Keywords: *parametric design, urban design, urban design practice, methodology, workflow*

INTRODUCTION

Many forms of urban design are distinct from architectural design in that they do not have a clear audience, nor a tangible output. Rather, they act as communication media to communicate design intents to a multitude of stakeholders and interest groups. And as such, they typically define a set of loose design guidelines to be observed, rather than precise design specifications. This is true for many masterplans, urban redevelopment plans, as well as for district plans, whether for greenfield development or brownfield redevelopment.

Such plans therefore often work by exemplification, offering a host of examples of how the plan might be implemented, or by scenarios, offering different design alternatives to be implemented. They may also present sets of more abstract restrictions (i.e. build-to lines, building envelopes, land-use contingencies, etc.) which subsequent building designs must comply with.

Examples, scenarios and restrictions have traditionally been visualised by way of static graphics in the form of diagrams, projection drawings, perspective renderings, reference photos, etc. However, by the advent of parametric design software, more dynamic forms of visualisation have been made possible, both during the development and subsequent presentation of urban design.

Research Outline

Building on previous work on establishing a parametric urban design framework for site design, including the parametric design of site layouts, building envelopes and facades (Steinø & Obeling 2014, Steinø 2017), this research gives an account of applying this framework to an actual urban design project for the design of a masterplan for a suburban residential area. In a form of action research, the researcher operated as a sub-consultant in collaboration with an established planning consultancy to implement a parametric urban design workflow. As such, the aim of the research was to test the parametric urban design framework in a practice setting, in order to understand its potential advantages and/or shortcomings in urban design practice.

Theoretically, a parametric urban design workflow has several advantages:

1. It enables the dynamic and interactive production of data output and geometric output (2D/3D models).
2. It enables iterative design cycles to facilitate design collaboration between design professionals.
3. It facilitates the dynamic generation of multiple design scenarios in the context of live scenario building at stakeholder workshops.
4. It allows for a more or less automated generation of a host of graphics from diagrams over projection drawings to perspective renderings with limited or no need for post-processing.
5. It provides a pipeline for the generation of videos and VR experiences, based on procedurally generated 3D environments.

A parametric urban model is generated from parameters which are set to specific values. Thus, the model can easily be modified by changing the values. As data (i.e. no. of dwellings, floor area ratios, land use by area, etc.) is linked to geometry, this allows for easy evaluation of different design scenarios against their associated data. This radically enhances design evaluation, as separate calculations are no longer necessary for each design iteration. This is highly relevant in urban design practice, where specific values must typically be met for different design criteria (parameters).

Different design professionals (i.e. architects, landscape architects, traffic and urban planners) focus on different aspects of urban design. A parametric model can easily be changed and is therefore capable of mediating the different design criteria of different design professionals in real time, through iterative design cycles.

In participatory design processes, lay person stakeholders are typically presented with 2-3 design scenarios as a basis for discussion. While the criteria defining the different scenarios are often oblique (as they have been predefined by the design professionals), scenarios are a practical necessity by conventional means of design. With parametric urban design however, the design may be altered through live scenario building, allowing for multiple design scenarios.

By conventional design methods, the production pipeline for the final graphics communicating the design may comprise a number of different graphic and CAD software applications. In addition, final graphics must be altered manually whenever last-minute alterations to the design are made. This results in reduced efficiency and high time pressure towards the end of the design process. As imperfect knowledge often leads to late alterations to the design in urban design, this is a likely scenario.

By a parametric urban design approach, the parametric urban model can be designed to automatically output different types of graphics, from diagrams over projection drawings to perspective renderings. Thus, it is capable of reflecting last-minute design alterations with no or limited extra effort.

Finally, with the advent of new game engine software such as Unity and Unreal Engine, new possibilities have emerged for the effortless generation of videos and VR experiences from parametric urban models. As a parametric urban model may be generated with a high level of detail with little effort, the work which is embedded in it may easily be used to provide a pipeline for the generation of videos and

Figure 1
User participation workshop. The parametric urban design model is visible on the screen

VR experiences. Video and VR represent new and enhanced modes of representation for urban design, offering new possibilities of exploring and understanding the design at hand.

In total, the aim of the research has been to explore these five potential advantages of a parametric urban design workflow in urban design practice. This was unfolded in the framework of a test case in the form of a project for the design of an actual masterplan for a new residential area of a small town. The researcher's contribution to the project was carried out as a sub-consultancy to an established urban planning consultancy. This was done using a software framework encompassing the parametric urban modeling software CityEngine, the game engine software Unreal Engine, and Photoshop.

Related Work

Several studies have been made to develop a methodological framework for parametric urban design. Most notably, shape grammars have formed the basis for such work by Beirão, Duarte, Gil, Stouffs and others in the context of the City Induction project. This body of work on parametric urban design encompasses three areas of investigation, formulation, generation and evaluation, and focuses in part on flexibility and variation (Beirão & Duarte 2005), GIS and spatial analysis (Gil & Duarte 2008, Beirão et al. 2008), urban patterns and grammars (Beirão et al. 2009, 2010), and tool development (Beirão et al. 2011, 2012). Shape grammars are also the basis for Paio & Turkienicz' (2010, 2011) analyses of historical Portuguese cities.

Different explorations have been made into the practical application of a parametric design approach to urban design and its related fields. Madkour et al. (2009) explore the application of parametric design to building design and city planning, while Ulmer et al. (2007) are interested in the application of parametric/procedural modeling to urban design and landscape planning. For their work, Ulmer et al. use CityEngine. This is also the platform used by

Kunze et al. (2012) for their work on implementing design code building typologies in parametric/procedural urban modeling.

Parametric urban design has obvious potentials for participatory design processes. This has been addressed by Jacobi et al. (2009), Kunze et al. (2010, 2011, 2012) and by Steinø et al. (2013).

Practice application of interactive visualisation and parametric modeling for urban design may address both public planning and private consultancy. Not many such studies have been made, however. One exception in the area of public planning is Dobson & Lancaric's (2003) somewhat older study for an interactive digital 3D urban model, which incorporates a variety of visual, graphic and numeric data to generate building scenarios to be presented online. Another exception is Schirmer & Kawagishi's (2011) more recent investigation of the application of CityEngine in architectural consulting. In this case, parametric urban design was used for visualisation, the creation of random subdivisions, and for typological testing.

METHODOLOGY

The main focus of the presented research was to explore a software framework which enables a fast and flexible workflow for a host of urban design tasks from massing studies to masterplans, capable of producing a variety of media types, from massing models and figure/ground maps, over land use maps and traffic diagrams, to detailed site plans and perspective renderings, all from the same parametric model. In addition to these traditional media types, the ambition was to use the parametric model for live scenario building at stakeholder workshops, as well as for animation videos and VR.

Based on previous research (Steinø & Obeling 2014, Steinø 2017), a small case study was conducted in order to analyse and classify typical site designs, building forms and facade schemas respectively for the specific task. From this analysis, scripts were coded to parametrically control variations to the design on these three levels. While still in its infancy, this body of code is capable of producing a large number of different site designs with architectural detailing, although not yet able to offer enough flexibility to cater for most desired design variations.

An important objective of the project has been to keep the software framework simple, in order to maintain the efficiency of the workflow. Hence, it was limited to:

- CityEngine for parametric modeling using the cga scripting language
- Unreal Engine for physics-based rendering and animation
- Photoshop for retouching and adding high detail single objects to renderings

For CityEngine, the input used is open GIS data in the form of 2D building polygons, street centerlines and terrain rasters, and cga scripts for model and data generation. The output from CityEngine is 3D models, 2D maps, data (floor areas, floor area ratios, land use, no. of dwellings, no. of parking spaces, etc.), and 360 VR images. For Unreal Engine, the input used is the 3D models generated in CityEngine, as well as various textures and other model assets. The output from Unreal Engine is rendered site plans, perspective views (stills) and video animations. For Photoshop, both the input (from Unreal Engine) and the output is rendered images.

Design revisions are a recurring element in all phases of design practice. Ideally, the design model should therefore remain in the parametric modeller (in this case CityEngine) for as long as possible to allow for parametric modification. However, as the render functionality of CityEngine is currently substandard, another software (in this case Unreal Engine) is used to this end. However, more diagrammatic media types such as land use and figure/-ground maps may still be rendered satisfactorily in CityEngine, leaving only a subset of the required media types to be finalised in Unreal Engine.

Figure 2
Mock-up parametric masterplan

Figure 3

Figure 4

Figure 5
Hand sketch produced by the main consultant

TEST CASE RESULTS

The methodological framework described above was put to use for the design of a masterplan for a new suburban residential area of a small municipal town in the Northern part of Denmark. The parametric design work was carried out as a sub-consultancy to a planning consultancy who was commissioned by the municipality to develop the masterplan. The lead professionals involved from the planning consultancy were a land surveyor (project manager) and an architect. As part of the design process, a series of meetings were held with professionals from the municipality, as well as two user participation workshops with landowners from the affected areas (fig. 1).

The aim of the collaboration was to use parametric design to test and ultimately visualise

- The overall masterplan in the context of existing development
- A detailed site plan with building types, greenspaces with vegetation elements (trees and hedges)
- Possible variations of building typologies in select parts of the masterplan
- Development phase diagrams
- A birds eye perspective rendering of the entire development area
- A number of perspective renderings of prototypical elements of the masterplan

Prior to the design process, the researcher/subconsultant presented a mock-up parametric masterplan (Fig. 2) and conceptual designs for different subdivision schemes (Fig. 3 and 4) to the main consultant, in order to introduce the principles of parametric urban design and their possible application to the project to the main consultant. The advantages of the parametric urban design approach, including the linkage between 3D model and data, as well as the automated generation of final graphics were explained and discussed.

In the course of the design process, hand sketches were produced by the main consultant as a basis for the parametric design work (Fig. 5). Preliminary renderings of the parametric model were returned for discussion and further design development, in part to evaluate different design alternatives, such as the width and shape of a public green space (Fig. 6-8). For the first user participation workshop, a preliminary parametric 3D model was used for live scenario building to analyse and discuss different design alternatives (Fig .1). Once the design was near completion, the parametric model was migrated into Unreal Engine and some preliminary renderings were produced and presented to the main consultant to discuss and adjust the render quality. On this basis, graphics showing design variations (Fig. 9-11) and perspective renderings were produced in Unreal Engine.

A small video animation (not shown) was also produced for internal purposes to test this part of the workflow. While not part of the planned scope of work, the video was shared with the main consultant and ultimately shown at the second user participation workshop. Once the design was finalised, the described graphics were produced in CityEngine and Unreal Engine respectively. Some post-processing was done in Photoshop to some of the graphics, for retouching and adding high detail objects (Fig. 12-13).

While most of the final graphics could have been produced using the devised workflow, the main consultant chose to ultimately produce some graphics manually. Miscommunications based on an insufficient understanding of the parametric workflow on behalf of the project manager led to some frustration, as unexpected requirements for new types of graphics were introduced at a late stage in the process. In addition, the project manager was unhappy with the quality of some final graphics produced using the parametric workflow.

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13

Hence, while the workflow was carried out largely as planned, some additional graphics - the video animation - were made in addition to the agreed scope of work, while other graphics were ultimately rejected. And while some additional graphics could not be produced as they had not been planned as part of the workflow, an original idea to use VR during the first user participation workshop was abandoned. The latter was due to the project manager being uneasy about the value of VR in this context, as this was a technology which was unfamiliar to him.

DISCUSSION

As a professional activity, urban design practice is based on sets of best practice, established forms of collaboration and output conventions. Depending on the project type - i.e. massing or visibility studies, site designs, masterplans - urban design professionals typically work from past experiences which they adapt to the task at hand. As different project types require different sets of expertise, different professionals - i.e. architects, engineers, urban planners - may be involved in the process. And once the work is done, it is presented to the client (whether private or public), typically in the form of reports with text and graphics.

Urban design graphics range from abstract diagrams (showing circulation, green space, density, etc.) over projection drawings (plans, sections, elevations) to perspective renderings with varying degrees of photo realism. Such graphics are typically made using a range of graphic and CAD software, often in sequence in some form of software framework. Whether developed from conventional hand sketches or simulation software, such graphics are based on input from the different professionals involved in the proces.

As such, urban design practice represents an ecosystem of practices, professionals and graphics, based on conventions established through experience. Hence, introducing parametric urban design methods is not a matter of simply adding another tool to the toolbox. It is likely to impact all elements of this ecosystem, as it not only introduces more 'efficient' ways of working, but potentially changes both established practices, forms of collaboration and out-

Figure 14
Final masterplan perspective rendering. Compare fig. 2 and 5

put types. In other words, it is likely to disrupt the very professional culture of urban design practice.

This became evident in the test case presented here. The project manager initially envisioned parametric urban design as a form of design optimisation tool. Given the large amount of potential parameters and variables, this is (as of yet) not feasible in urban design. It took some explaining to establish a more realistic understanding with the project manager as to the potential of parametric urban design. That is, that while the overall design principle still needs to be conceived architecturally by a human designer, the parametric model may, one the one hand, generate associated data (no. of dwellings, floor area ratios, land use by area, etc.) for design evaluation and, on the other hand, generate variations of the design based on the parameters which have been incorporated for design iteration.

The generation of associated data within the parametric urban design model seemed to the researcher/sub-contractor as one of the main 'selling points' of a parametric urban design approach. During the design process, the researcher/sub-contractor provided a range of data with the 3D models and asked whether they were relevant. However, the main contractor did not respond to this and never seemed to take much interest in this data, despite the fact that it was information which had influence on the plan and which had to be submitted as part of the contract and therefore ended up being produced manually.

CONCLUSION

The action research case study accounted for in this paper put a methodological framework for parametric urban design to test in a real-life setting in collaboration with a professional planning consultancy. The framework was designed on the basis of anticipations about the task at hand and presented to the main consultant at the beginning of the process. While parts of the framework proved to work, others did not. The unsuccessful parts of the framework failed in part due to misconceptions about the nature of the parametric workflow on behalf of the project manager, and in part due to the researcher/subcontractor failing to meet the graphic aspirations of the main consultant. And while an animation video was produced and used which was not part of the planned scope of work, diagrams which were originally planned were ultimately produced manually.

As a form of action research, the case study was based on the premise that the main consultant ultimately had to deliver a professional product to his client. In the project manager's judgment, this required parts of the work to be produced using conventional techniques. This was true, both for some graphics and for the choice of not introducing VR at the user participation workshop.

In conclusion, both the main consultant and the sub-consultant/researcher bore parts of the responsibility for this result. While the main consultant did not quite understand parts of the methodological framework (the nature of the workflow, the value of associated data) and did not have confidence in the value of VR for participatory processes. The subcontractor/researcher on the other hand, failed to deliver satisfactory graphics for diagrams. He also failed to demonstrate VR in action to the main contractor and hence to illustrate its potential.

Despite these failures, the overall results were successful. It was shown that a parametric urban design workflow is in fact functional and does produce several of its theoretical advantages. Design alterations could in fact be incorporated even late in the design process, without causing significant extra work. Relevant associated data could in fact be produced even if it was not taken into consideration. And a workflow from CityEngine into Unreal Engine could in fact be put to use with very little effort, in order to produce an animation video.

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eCAADe

www.ecaade.org

eCAADe (Education and Research in Computer Aided Architectural Design in Europe) is a non-profit making association of institutions and individuals with a common interest in promoting good practice and sharing information to the use of computers in education and research in architecture and related professions. The organization was founded in 1983, and organizes an annual conference, which is hosted by a different member University each year. eCAADe initiated and manages the very successful CumInCAD archive of research publications in the field of Computer Aided Architectural Design. **CumInCAD** is a valuable resource for researchers, educators and others in the field. eCAADe has also collaborated with sibling associations to create the International Journal of Architectural Computing (IJAC).

SIGraDi

www.sigradi.org

SIGraDi (The Iberoamerican Society of Digital Graphics) is a non-profit association that brings together architects, urban planners, designers and artists linked to digital media. Its main goals are to contribute to the academic debate on digital media and their applications, promote the production and advancement of scientific knowledge in general, and stimulate research and education in the current context of major technological changes.

Sibling Associations: ACADIA CAADRIA ASCAAD CAAD Futures

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With origins dating back to the XVIII century, the **University of Porto** (UP) is currently one of the most relevant education and research institutions in Portugal. Close to 31,000 students, 2,300 teachers and researchers along with 1,700 administrative staff attend its 15 schools and 69 scientific research units, spread across three University Campus located in the city of Porto.

As an organic unit of the UP, the **Faculty of Architecture of the University of Porto** (FAUP) is one of the most prestigious Portuguese and European institutions of education, research and innovation in Architecture. Located in Polo III (Campo Alegre), the building complex of FAUP is one of the most emblematic creations of Álvaro Siza's career, who was awarded with the Pritzker Prize 1992, and is an Emeritus Professor at FAUP. The School offers high quality courses, which include a Master Degree in Architecture (MIARQ), a PhD Programme in Architecture and an Advanced Studies Course in Architectural Heritage. The Center of Advanced Studies in Architecture and Urbanism (CEAU) manages the research activity at FAUP, which integrates the Digital Fabrication Laboratory (DFL) among other research groups. FAUP is thus a stimulating academic environment bringing together the traditions and the innovations in the discipline.

Today, we live in a moment of profound and accelerated changes in the way we perceive and interact with the world, which many authors do not hesitate to call as "the 4th Industrial Revolution". Extraordinary advancements in areas like mobile communication, artificial intelligence, big data, cloud computing, blockchain, nanotechnology, biotechnology, facial recognition, robotics or additive manufacturing are fusing the physical, biological and digital systems of production.

Such technological context has triggered a series of disruptive concepts and innovations, like the smartphone, social networks, online gaming, internet of things, smart materials, interactive environments, personal fabrication, 3D printing, virtual and augmented realities, drones, self-driving cars or the smart cities. All together, they are drawing a radically new world.

Like in the past, if the world changes, the discipline of architecture cannot remain indifferent. It must understand and adapt to the new circumstances and also, why not, orient some of the undergoing transformations. Since digital technologies are at the core of the emerging paradigm, the eCAADe and SIGraDi Associations joined their annual Conferences in 2019, and invited researchers, professors, professionals and students in Porto at FAUP to debate how digital technologies are shaping the place and role of architecture in the age of the 4th Industrial Revolution.

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