The next city

New technologies and the future of the built environment

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Volume Editors

Gabriela Celani
University of Campinas
E-mail: celani@fec.unicamp.br

David Moreno Sperling
University of São Paulo
E-mail: sperling@sc.usp.br

Juarez Moara Santos Franco
University of Campinas
E-mail: jfranco@fec.unicamp.br
Preface

Since 1985 the Computer-Aided Architectural Design Futures Foundation has fostered high level discussions about the search for excellence in the built environment through the use of new technologies with an exploratory and critical perspective. In 2015, the 16th CAAD Futures Conference was held, for the first time, in South America, in the lively megalopolis of Sao Paulo, Brazil. In order to establish a connection to local issues, the theme of the conference was "The next city". The city of Sao Paulo was torn down and almost completely rebuilt twice, from the mid 1800s to the mid 1900s, evolving from a city built in rammed-earth to a city built in bricks and then from a city built in bricks to a city built in concrete. In the 21st century, with the widespread use of digital technologies both in the design and production of buildings, cities are changing even faster, in terms of layout, materials, shapes, textures, production methods and, above all, in terms of the information that is now embedded in built systems.

Among the 200 abstracts received in the first phase, 64 were selected for presentation in the conference and publication in the Electronic Proceedings, either as long or short papers, after 3 tough evaluation stages. Each paper was reviewed by at least three different experts from an international committee of more than 80 highly experienced researchers. The authors come from 23 different countries. Among all papers, 10 come from Latin-American institutions, which have been usually under-represented in CAAD Futures. The 33 highest rated long papers are also being published in a printed book by Springer. For this reason, only their abstracts were included in this Electronic Proceedings, at the end of each chapter.

The papers in this book have been organized under the following topics: (1) modeling, analyzing and simulating the city, (2) sustainability and performance of the built environment, (3) automated and parametric design, (4) building information modeling (BIM), (5) fabrication and materiality, and (6) shape studies. The first topic includes papers describing different uses of computation applied to the study of the urban environment. The second one represents one of the most important current issues in the study and design of the built environment. The third topic, automated and parametric design, is an established field of research that is finally becoming more available to practitioners. Fabrication has been a hot topic in CAAD conferences, and is becoming ever more popular. This new way of making design and buildings will soon start affecting the way cities look like. Finally, shape studies are an established and respected field in design computing that is traditionally discussed in CAAD conferences.

Hosting CAAD Futures conference was a great honor to us. Enjoy this great selection of papers.

São Paulo, July, 2015

Gabriela Celani
David M. Sperling
Juarez M. S. Franco
Acknowledgements. The editors are very grateful to Professors Bauke de Vries and Tom Kvan, CAAD Futures’ presidents, for their constant support throughout the entire process of evaluating papers for this book and preparing the conference. We also thank all the scientific committee members for their competent reviews and helpful comments to the authors, which resulted in the highest academic standard of the papers selected. Finally, the conference would not have been possible without the sponsorship of the following Brazilian public research foundations: the National Council for Scientific and Technological Development (CNPq), the Coordination for the Improvement of Higher Education Personnel (CAPES), and the São Paulo State Research Foundation (FAPESP, process number 2014/07186-5). We also thank the University of Campinas' Library staff, for the editorial support, the University of São Paulo's Office of the Dean for Research, for its support to the conference exhibition, MASP's team, for their kind assistance during the preparation for the event, Jarryer de Martino, for his fine graphic design, Abílio Guerra, for spreading the word and all the other people who directly or indirectly helped making this conference happen.
Keynote speakers

The papers in this book cover three aspects of design computing: its origins, new research frontiers and applications in practice. In a similar way, the conference keynote lectures were grouped under the following topics: “CAAD in History”, with Arivaldo Leão de Amorim (Brazil) and João Magalhães Rocha (Portugal), “CAAD in Research”, with Axel Kilian (Germany/USA) and Jane Burry (UK/Australia), and “CAAD in Practice”, with Milos Dimic (Serbia/Germany) and Caroline Bos (Netherlands). When selecting the speakers we tried to be as inclusive as possible, with young and experienced men and women from academia and practice, representing institutions from South and North America, Europe and Asia/Pacific.

Day 1: CAAD in History

Arivaldo Leão de Amorim
Federal University of Bahia

Arivaldo Leão de Amorim has graduated in civil engineering (1977) and architecture (1982) at the Polytechnic School and at the Faculty of Architecture of Federal University of Bahia (UFBA), respectively. He did his Master (1990) and PhD (1997) courses on transportation engineering at the Polytechnic School of Sao Paulo University (USP). Presently, he is full professor at the Faculty of Architecture of UFBA, and he has worked on applications of digital technologies for Architecture, Urbanism and Construction. In 1992, together with Prof. Gilberto Corso, they created LCAD – Laboratory of Advanced Studies on Architecture, City and Digital Technologies (since 2014), an important national reference in this area. His works and interest cover Computer Aided Architectural Design (CAAD), Building Information Modeling (BIM), Cultural Heritage Documentation, and Urban Planning on education. He has organized a set of conferences related to these subjects and produced some related papers. Besides, his collaborative work with several national universities, he also has collaborative agreements with the Institute of Photogrammetry and Remote Sensing (IPF) of Karlsruhe Institute of Technology (KIT), in Germany, and with the Dipartimento di Ingegneria Civile Edile e Architettura (DICEA), of the Universita Politecnica della Marche (UNIVPM), in Italy.

CAAD History in Brazil

Arivaldo Amorim's lecture will be titled "CAAD History in Brazil". He will present the evolution of use of the computers in the AEC area to the current CAAD applications, starting with the context of the contested national law of market reserve.
of information technology that contributed to the delay of the popularization of computers in the country, especially its use in architecture; the first experiments and uses with CAD and the conferences in the 1980s; a panorama of the 1990s covering the first teaching experiences facing architecture; the compulsory computer education in architecture by law; the events and the emergence of the first research groups; the popularization and universalization of CAD use in offices and schools of architecture in the 2000s, as well as the consolidation of research groups; and finally the maturity of the area with the diversification of subject research and strengthening of the research groups from 2010 on. He will conclude with an assessment of the panorama of the national production from papers presented at conferences, thesis and dissertations, and the research groups registered in CNPq's directory.

**João Magalhães Rocha**, University of Evora

João Magalhães Rocha teaches at the Department of Architecture at the University of Évora (UE), Portugal. He earned a M.Sc from Columbia University (GSAPP) New York (1995) and completed his PhD at the Massachusetts Institute of Technology (MIT) at the Design and Computation Group. He taught at the Pontificia Universidad Católica (PUC) at Santiago, Chile (1996), at MIT as a teaching assistant (1998-2002) and received a Post-doc Fellowship from the Paul Mellon Centre for Studies in British Art in London (2008). He was recipient of a Harold Horowitz Student Research Award (MIT) and was a research Fellow at Cambridge University, UK. In addition he holds a professional degree in architecture from the Technical University of Lisbon (FAUTL). Currently is Adjunct Director of the Department of Architecture at Évora University, he has lectured widely and published broadly and his research deals primarily with the development of computation in relation to architecture both from a historical and practical perspective. As member of the UNESCO Chair for Intangible Heritage and Traditional Know-how (UE) he pursues work regarding Portuguese heritage at the Maghreb area. His book, War Science Architecture: From World War II to Architecture Computing will be released during Spring 2015.

**War Science Architecture**

**From World War II to Architecture Computing**

João Rocha's lecture addresses the development of computer technology from the dawn of World War II till the inception of the first research Centers on Design Computing. In an era where the term Digital Architecture emerges globally with impacts on every field of the architectural discipline it urge to draw a map that enlighten the origins of this new thrilling endeavor. The lecture depicts on research investigating the foundation, development and advances of computing technology when applied to architecture. Deriving from theoretical, practical an archival research the author provides a new cultural and historical framework, which contextualizes the birth of architecture computing initially in the UK and later in the USA.
Axel Kilian is an Assistant Professor at the Princeton University School of Architecture. He previously taught Computational Design at the Department of Architecture at MIT and at TU Delft. In 2006 he completed a PhD in Design and Computation at MIT on design exploration. In addition he holds a Master of Science from MIT and a professional degree in architecture from the University of the Arts Berlin. Axel Kilian has lectured widely and published extensively. His publications include the Architectural Geometry book from 2007 with coauthors H. Pottmann, A. Asperl, M. Hofer. Axel Kilian was a longtime contributor to the Smart Geometry event series from 2003-2010 as well as co-chair of the inaugural Advances in Architectural Geometry conference in 2008, and member of the advisory committee for the Design Modelling Symposium in 2011 and 2013, as well as frequent reviewer for journals and conferences in the field of computational design. He contributed to the concept car design studio of William Mitchell in the Media Lab's Smart cities group from 2003-2006. In addition he is the founder of the design consultancy designexplorer.net. His latest research focus is on embodied computation, the continuation of computation in the physical realm.

**Embodied Computation**

Axel Kilian's lecture is titled Embodied Computation. In some engineering systems such as quad copters there is a shift from systems with mechanical complexity for control towards algorithmic complexity paired with simpler mechanics. This allows for greater flexibility and a continued adaptation of the systems post deployment and therefore a chance for the design process to continue into the artifact itself. In parallel in robotics sensor feedback and open loop controls are slowly being integrated into the fabrication process that offers the opportunity to assign material more agency in the process of fabrication. To understand materials as the embodiment of computational processes and to link these physical processes more with the computational processes of design and view define the design process as open ended process beyond the completion of the physical artifact is the challenge that will be discussed on an experimental scale. The implications of these changes are particularly fascinating at an architectural and urban scale both for the creation of future constructs and the refurbishing of existing structures as networked and computationally enabled entities.
Jane Burry, Royal Melbourne Institute of Technology

Jane Burry is an architect and Associate Professor of Architecture and Design in the School of Architecture and Design, RMIT, where she directs the Spatial Information Architecture Laboratory, SIAL. Set up to foster transdisciplinary research and education, SIAL is home to twenty PhD candidates pursuing design practice-led research, many in association with government and industry-funded projects. Jane also established and coordinates RMIT’s Master of Design Innovation and Technology program. She has practiced, taught and researched internationally, including involvement as a project architect in the technical office at Antoni Gaudi’s Sagrada Familia church in Barcelona and the design of many less prominent built works. She has over sixty publications. Her research focuses on mathematics in contemporary design. Jane is lead author of The New Mathematics of Architecture, 2010. Within SIAL she is currently engaged in research into advanced design and construction and the enfolding of analysis feedback into early, responsive and interactive design and prototyping. Related to this work, she edited the book Designing the Dynamic, 2013, and is currently investigating the Integration of Architectural, Mathematical and Computing Knowledge to Capture the Dynamics of Air with colleagues in architecture, mathematics, computing and engineering.

Researching the Sensate City

Jane Burry's lecture will be titled Researching the Sensate City. As a theatre for collective human life, the city is both an expression of permanence and solidity and an ever-transforming environment. Increasingly, the boundaries between the fabric of the city and the animate are blurring. The built environment sees, it knows and communicates where we are, can sense where we are going. It has the potential to feel and respond usefully to changes in the ambient environment. Although built architecture remains largely static, or only subtly dynamic, the city fabric nevertheless encounters and interacts with some of the most complex and unpredictable dynamic data and information streams. The very stasis of buildings can make their interaction with ambient flows more unpredictable. Design research for the "next city” calls for a phenomenal approach to the qualities of atmosphere, sound, heat, air movement, humidity and human interaction that acknowledges the subtlety of the feedback cycles informing an increasingly sensate and responsive city. The presentation will explore novel ways to collect and process real time data or simulate behaviour to create design feedback environments in which designers can build their own intuition while designing.
Day 3: CAAD in Practice

Milos Dimcic, Programming Architecture

Milos Dimcic graduated from the Faculty of Architecture, Belgrade, in 2006. He continued his studies in Stuttgart, Germany, where he finished his PhD in 2011, under the guidance of Prof. Dr.-Ing. Jan Knippers. During the studies he also worked at the Knippers Helbig office in Stuttgart. He has more than 8 years of experience in combining architecture, structural engineering and programming. Since 2007 he has been developing automation methods used in some of the world's famous large scale projects. In 2009 he programmed the largest parametrically generated facade and structure in the world. In 2011 he founded Programming Architecture and he has being developing different types of software (including free plug-ins) for very diverse and interesting projects all around the world. Some of the projects he contributed to since 2007 are: Bao'an Airport – Shenzhen, China (M.Fuksas), EXPO Axis - Shanghai, China (SBA Architects), Institute of Peace, Washington D.C, USA (Moshe Safdie), KAPSARC Research Center, Riyadh, Saudi Arabia (Zaha Hadid), Crystal Hall, Baku, Azerbaijan (GMP), and many others.

Artificial Intelligence in Architectural Praxis

Milos Dimcic's lecture will be titled Artificial Intelligence in Architectural Praxis. In this day and age, in architectural and engineering offices, we are using computers as automation tools. We write algorithms and use machines that make our work more efficient in terms of speed and strength. Recently, there has been a lot of discussion about technological singularity - the moment when artificial intelligence (AI) surpasses human intelligence. This is known as strong AI. We are still far away from that moment, but on our way there we are creating software that goes beyond a tool, and slowly becomes something known as weak AI. We are entering an era in which highly specialized software is not our servant; it is our co-worker, our advisor. The lecture will focus on practical applications of algorithms that give answers to questions you cannot answer yourself, thus helping you reach creative and optimal design. On the examples of some of the largest and most complex projects in the world, methods of simple automation will be demonstrated, but also techniques already describable as weak AI. After discussing the power of such algorithms, the focus will be shifted on their future, which is already being written (coded).
Caroline Bos studied History of Art at Birkbeck College of the University of London and Urban and Regional Planning at the Faculty of Geosciences, University of Utrecht. In 1988 she co-founded Van Berkel & Bos Architectuurbureau with the architect Ben van Berkel, extending her theoretical and writing projects to the practice of architecture. Realized projects include the Erasmus Bridge in Rotterdam, museum Het Valkhof in Nijmegen and the Moebius house. In 1998 Caroline Bos co-founded UNStudio (United Net). UNStudio presents itself as a network of specialists in architecture, urban development and infrastructure. Current urban development projects include the restructuring of the station area of Arnhem, the mixed-use Raffles City in Hangzhou, a masterplan for Basauri, and the design and restructuring of the Harbour Ponte Parodi in Genoa. Caroline Bos has taught as a guest lecturer at Princeton University, the Berlage Institute in Rotterdam, The Academy of Fine Arts in Vienna and the Academy of Architecture in Arnhem. In 2012 she was awarded an Honorary Professorship at the University of Melbourne's Faculty of Architecture, Building and Planning. Central to her teaching is the inclusive approach of architectural works integrating virtual and material organization and engineering constructions.

Next City, next Stop: Doha
Design strategies for the Qatar Integrated Railway Project

Caroline Bos's lecture will be titled Next City, next Stop: Doha - Design strategies for the Qatar Integrated Railway Project. In 1999 UNStudio launched the notion of deep planning, an exploration of the relation between architecture, urbanism and infrastructure, noting: „The new architect faces a new assignment. Increasingly involved as the architect is in the realisation of bridges, motorways and urban revitalisation plans, alongside houses, offices and public buildings, the traditional procedures of practice are becoming inadequate. Urban nodes and infrastructure are some of the most important questions facing architecture at the moment.“ („Move“, Van Berkel, Bos, 1999). For UNStudio, then, the blurring of the traditional distinctions between categories, typologies, and scales (city-nature, public-private, and global-local), is essentially connected to the real and concrete places that facilitate the increased mobility and access that characterizes our time. The next stop in the next city is a node in the networked city, and designing an infrastructure network requires a network approach to designing and building. The realization of a contemporary space of flows thus necessitates a policy-aware, flexible, spatially-technical innovative, networked approach. This talk will use the design process of the Qatar Integrated Railway Project (QIRP) to focus on the question which are the instruments and design tools that allow the profession to effectively respond to „networked infrastructures, technological and the urban condition“?
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Design knowledge and CAAD conferences
A place at the table for research through design

Jules Moloney

1Deakin University
jules.moloney@gmail.com

Abstract. This paper addresses an issue that has been omnipresent in the history of CAAD research: the tension between scientific method and the design discipline in which it operates. Outside the CAAD community, research through design is being undertaken by a new generation. Through a discussion of research methodologies, a survey of CAAD activity and the examination of design projects, it is proposed that this provides a valuable opportunity to redress the balance between scientific and designerly modes of research and in so doing engage with a new generation of design computing researchers.

Keywords: Research Through Design, Methods, CAAD History.

1 Introduction

2015 marks the thirtieth anniversary of the establishment of CAAD Futures. It is also the twentieth anniversary of CAADRIA, while ACADIA, ECAADE and SIGRADI were founded respectively 34, 32 and 18 years ago. These are substantial periods of activity and the organizations have been highly successful at advancing research and teaching of computer aided architectural design around the globe. My first engagement with these communities was attending the 1995 CAAD Futures conference in Singapore, on route to my first academic job after a decade in architectural practice. In many ways the 1995 conference was seminal: with the title of The Global Design Studio, the conference showcased virtual design studios enabled by the newly available ‘internet’; and a generation of researchers from the pioneering 70’s and 80’s reflected on progress; including Tom Maver’s infamous CAAD’s Seven Deadly Sins [1]. Twenty years on, another generational shift has occurred, alongside the ubiquitous use in practice of what were considered advanced computing techniques such as generative algorithms, real time visualization and computer aided manufacture. Given the majority of design is now undertaken through the computer, it is timely to consider the role and relevance of specialist CAAD research organizations. The position explored here is that the contemporary users of CAAD – young designers, practitioners and consultants – have much to offer. One potential way to engage with this new generation is to be more accommodating in the recognition of designing as a significant research activity. This position recognizes that much of the
cutting edge computational activity now occurs through expert users in the latter stages of their education or as recent graduates in practice.

This presentation is organized in three sections. In the first I note the dual heritage of CAAD- science and architecture - and locate the tension this has caused in relation to research method. From this I explore the establishment of research through design outside the CAAD community, through the contributions by Downton and Blythe. The framework has settled around a tripartite understanding of research: about (the methods, media and techniques that are used to carry out design); for (research that will enable design such as material, construction and performance simulation); and through design (where a project embeds significant understanding or insight that can in turn inform subsequent design research). A second section presents analysis of a survey of publications from the CAAD community since 1994, which locates the spread between research about, for and through design. This enables a comparison of activity within CAADRIA, ACADIA, eCAADe and CAAD Futures conferences. The final section examines examples of research through design, identifying a range of approaches. The aim of the paper is to stimulate discussion on how to engage the current generation of designers, who through innovative adaptation of digital technology are, arguably, the new experts.

2 Design Research Methods Inside and Outside CAAD

In a paper entitled the Dual Heritage of CAAD Thomas Kvan locates the founding of CAAD in science and the creative arts, and the tension between computational logic and the creative practices of designing.

‘On the one hand, we find ourselves in the culture of design in which discovery is observed as an ineffable act of creation, tested only in its manifestation. On the other hand, the artifacts of our research must be expressible in the definitive and unambiguous clarity of data and procedures, to be evaluated in the integrity of their reasoning.’[2]’

Research methods are well established in relation to the scientific legacy and provide a robust and well established mechanism by which to evaluate quality. However, where designing as the method to undertake research is foregrounded, there is not the same level of agreement. In a series of CAADRIA presentations between 2009 and 2011 Thomas Fischer discussed the non-acceptance of research through design as a methodology within the CAAD community. Fischer highlighted the tension between the scientific bias of CAAD research and the typically subjective and circular methods used by designers. He locates alternate approaches to causality as the key issue, proposing that there are positives and negatives from an emphasis on linear (scientific) causality and circular (designerly) causality. His analysis is summarized by
way of a useful diagram (Figure 1) that articulates the problem for CAAD researchers. While circularity may lead to novel, exciting and adaptable outcomes, the approach is unpredictable, instable and unreliable. Hence as Fischer states, 'Much of CAAD, and neo-positivist scientific research in support of it, are preoccupied with the deployment of techniques developed to detect and enforce linear causation' [3]. This is reinforced by guidelines for paper reviewers that often include the requirement that the methods should be stated such that they can be reproducible. This requirement, while appropriate for linear scientific based methods, is typically not well articulated by those adopting circular design methods. Moreover, the emphasis on reproducibility or repeatability, while vital for science, is at odds with a design methodology that typically is either deliberately seeking a novel outcome, or the particular context will generate the novel redeployment of a design precedent.

![Figure 1](image-url)

**Fig. 1.** The polar distinction between linear and circular causality (Fischer, 2010)

Fischer cites the work of Nigel Cross, who is a key figure in the establishment of research through design outside the CAAD community. Cross in his seminal *Designerly Ways of Knowing* [4] set in 1984 a challenge for the design disciplines to develop an intellectual culture that can demonstrate standards of rigor that match those of the sciences. This challenge has been gradually taken up within the architectural design disciplines and while not fully mature, there is a growing body of thinking and exemplar research. At the vanguard are two institutions – the Bartlett School of Architecture and the Royal Melbourne Institute of Technology. Both have well established Doctoral programmes undertaken ‘by project’, where the outcomes are typically a series of designs interwoven with reflective commentary, which situates the design in relation to precedent and projects the trajectory for further design. While there are a growing number of publications articulating aspects of this agenda, Peter Downton’s *Design Research* provides (to my mind) a rigorous articulation of research through design, as distinct from research about or for design. Research about design focuses on the methods, media and techniques that are used to carry out design. This form of research will be very familiar to the CAAD community as arguably, research *about* the impact of the computer on architecture is the very genesis for the
identification of CAAD as a distinct field. Our proceedings and journals are thick with analysis of the impact of techniques enabled by computation and the methods (survey, interview, graphic analysis etc.) are well established. Alongside this, according to Downton’s study, research for design encompasses a distinct body of research that is undertaken to enable design. This includes site analysis, material and technology studies, and the building performance modelling, simulation and data analysis typically carried out in Architectural Science. Again, this mode of research is central to CAAD and the methods (empirical testing, calibration, etc.) are well understood and articulated by researchers. The third category of design research is underpinned by the logic of Downton’s opening sentence to his book.

‘Design is a way of inquiring, a way of producing knowing and knowledge; this means it is a way of researching.[5]’

Research through design typically examines a specific context to conceive and develop an architectural outcome that may be eventually realized, or it may be a ‘paper’ project produced for an ideas competition and/or as part a thesis. Presuming CAAD researchers have undertaken an architectural education and or worked in practice, designing will be familiar, albeit I suspect few would consider this a research activity in itself. As articulated by Fischer, research through design, without some form of scientific validation, would appear to be problematic for much of the CAAD community. According to Downton’s RMIT colleague Richard Blythe, the key to conceiving/designing as research is the critical reflection that accompanies and informs the design. He identifies three forms of reflection at play: reflection on previously completed designs; the intuitive reflection that accompanies the active design stage; and reflection that projects forward from the current project to suggest new designs. These three frames are identified separately as a way to understand the nuances of designing, but according to Blythe they are present simultaneously when designing, to produce a sophisticated ‘synthesised synthetic space’ of research inquiry. Arguably, to meet the standard requirement for research that results are transmitted to others, the design researcher would need to articulate the reflective process as a commentary on the design. It is at this point that some difference can be perceived between the RMIT approach and that of the Bartlett, particularly in relation to the role of writing in research. For Jonathan Hill, Director of the Bartlett PhD programme, design research ‘has two inter-related elements of equal importance—a project and a text—that share a research theme and a productive relationship.[7]’ Thus the contribution to knowledge and its transmission to other researchers is through a more or less equal weighting of text and design artefact (drawing, computer model, video etc.). This contrasts with the stance by Downton that design knowledge ‘has the distinct character of being embodied in the process of designing itself’ and that the ‘knowledge produced in design is stored, transmitted and learnt through works’[8].
locate two points between which there is much middle ground. For example, our one
year Masters thesis programme at VUW operates on guidelines of 75% weighting to
the design component and 25% to the accompanying text (typically 12,000 words).
We have found this strikes a balance between emphasizing the primary mode of
research is communicated with design representations, but that the expectation is that
critical reflection will be substantive: locating the project in relation to the particular
design scope; and communicating the insight / knowledge achieved in the thesis.

In summary, outside the CAAD community there is a substantive intellectual
culture that articulates methodologies, critique and precedent for research through
design. This culture is still maturing and there is a valuable plurality of modes of
operation within different parts of the worlds: the RIBA have identified guidelines for
conceiving research in professional practice; there is a shift from individual design
thesis to a collaborative research studio model in many US schools; while some
Scandinavian researchers have explicit expectations for designing as research. There is
substantial momentum—for example in the three schools of architecture in New
Zealand where the final year of study is a full thesis, over 500 Design Research
Mastersthesis have been completed in the last four years. This breadth and depth of
activity provides an opportunity and a challenge for the CAAD community.

Provocatively titled *There is No such Thing as Digital Design*, Neil Leach, in effect,
predicts the demise of organizations such as ACADIA [9]. From this perspective,
where most design is computational and much of the technical advances are now
occurring within practice and the design studio, what role will traditional CAAD
organizations play? My view is that the acceptance of research through design
provides a valuable opportunity to redress the balance identified by Fischer, and
refresh the established CAAD organisations. The challenge is to find ways in
which the positives of circular (designerly) causality and linear (scientific) causality
can mutually inform a new generation of CAAD research.

3 Trends within CAAD research 1984-2014

As a way forward, this next section tests Fischer’s observations that research through
design has been marginalized by the dominance of scientific research paradigms and
methods. This is undertaken by a targeted survey of publications since 1994 taking in
CAAD Futures, ACADIA, eCAADe, CAADRIA and SIGraDi. The aspiration to
obtain a useful snapshot of activity across such a timeline and involving five different
organizations, has proved challenging. While Cumincad provides an extremely useful
resource of all the relevant publications, there is no rigorous cataloguing system in
place. The aim at the start of the survey was to use Downton’s classification of
research about, for and through design to identify trends over time and any points of
difference between each of the organizations. This would be reliant on the consistent
use of keywords across thousands of papers, and it soon became apparent this was not
the case. In order to progress a trial and error approach was utilized, using keywords that appeared in publications that met Downton’s definitions. Through a process of trial and error a range of keywords were identified that enabled a sample of approximately 10%. The five sets of keywords used in the survey were prototype, project, practice, architectural design, design method, and design process. These keywords resulted in identifying 642 publications from a total of 6741 within the period 1994 – 2014. Each of these publications were categorized as primarily using a methodology about, for or through design. In most cases this could be ascertained through the abstract and where it was not obvious the full paper was reviewed. In some cases multiple modes of research were present and for these as long as there was a strong applied design component they were indexed as through design. A summary of the results of the survey are illustrated in figure 2.

Fig. 2. Indicative trends from 1994 – 2014 identified by keywords (prototype; project; practice; architectural design; design method; design process) indexed as about, for or through design.
It must be emphasized that the survey was intended to identify research through design as defined by Downton and to locate indicative trends over time and between CAAD organization. In this it serves its purpose, but it should not be considered authoritative. The results confirm expectation in terms of a dominance of research about design representing approximately 67%. Research for design was the focus of approximately 9%, likely reflecting the choice of keywords that avoided simulation, materials and others identifiable with such enabling research. Conversely, due to the targeting of key words, approximately 24% of the sample included a significant research through design component. While this cannot be considered definitive, some trends over time and differentiation between between organizations are identifiable. Below is a discussion of these trends with an interpretation in relation to the regional characteristics and tendencies, as observed by the author.

CAAD Futures has had minimal presence of papers that have a focus on research through design. It could be surmised that occurring bi-annually and typically attracting established researchers, that the scrutiny is higher and either the conference is not attractive to designers, or they do not get accepted. ACADIA has intermittent presence with a noticeable bulge in 2014. My observation is that ACADIA conferences have typically been more rigorous in selecting papers that directly address the yearly theme and preoccupation of the hosting institution(s), which might explain the intermittence. The hosts of the 2014 ACADIA conference—the University of Southern California - selected renowned designer Zaha Hadid as the main keynote and marketed the venue Los Angeles as ‘a global center of progressive design in architecture’ [10]. These factors are likely to explain the comparative number of research through design papers identified in that year. eCAADe has had the most consistent presence over the time surveyed, with a growing number of papers that foreground design as the vehicle for inquiry. My experience of attending multiple eCAADe conferences is that there generally is a greater range of topics and mix of academics and design professionals. It is also unique in that the review for acceptance is based on an extended abstract, rather than a full paper review. In contrast CAADRIA has until recently, not attracted designers or found research through design papers acceptable. This perhaps can be explained by the focus of CAADRIA on supporting young regional researchers and PhD students, who typically are working in institutions that have a tradition of science and engineering. These include Asian universities and a number of Australasian universities founded on design science, as evidenced by the long established Australian and New Zealand Architectural Science Association. SIGraDi has a similar trend to that of CAADRIA, with a noticeable increase in ‘hits’ in the last several years based on the keyword search. While I have not attended this conference, SIGraDi is differentiated from its sister organizations by an emphasis on graphics, rather than architecture per se. This perhaps, has resulted in less architectural design-led publications.
The intent of the survey was to evaluate Fischer’s observations that CAAD researchers (as quoted earlier) ‘are preoccupied with the deployment of techniques developed to detect and enforce linear causation’. This certainly would appear to be the case for CAADRIA, the conference in which Fischer presented his critique. In other institutions, notably eCAADe and at times ACADIA it would appear circular (designerly) research methods are to varying degrees present. However, CAAD Futures, considered by most the premier conference in CAAD, almost entirely consists of research that adopts scientific research methods.

The differentiation between regional organizations observed above is not necessarily an issue, and indeed may well be celebrated by many. It must also be noted that research through design is not universally accepted in mainstream architectural research. The motivation for highlighting the dominance of scientific paradigms in our organizations is that this would appear to be excluding much of the computer aided architectural design of the current generation. Their introduction to computing has typically occurred in a design focused environment, where the customization of software through graphic programming interfaces and experimentation with rapid prototyping techniques is the norm. While these young designers may be considered ‘mere users’, many are pushing the boundaries of design computing in a way that is innovative and directly relevant to practice.

4 Design Research Examples

This final section discusses two research through design publications located in the survey that illustrate a practice inspired project and a design thesis project. This is followed by a further example by a young designer outside the CAAD community. The objective is to briefly discuss some typical examples of research through design.

The first project will be known to many CAAD researchers – the Aegis Hyposurface©. The documentation of this design-led research was presented at the 2001 ACADIA conference. The project team was led by Mark Gaulthorpe who at the time was the director of a small practice dECOi Architects. dECOi won a competition that conceived a kinetic surface that could be used to visualize patterns, graphics and text as a dynamic relief. While there are precedents in the mechanical televisions of the 1920’s, this was the first time that an architectural surface would embed real time graphics. It has since stimulated a number of other prototypes and led to significant research into interactive architecture. The design led to a number of technical innovations in order to be realized, involving collaborative research from mathematicians, and multiple engineering disciplines – structural, rubber, adhesive, and pneumatic[11]. This is a seminal example of a design that has led to advances in computation and stimulated much further research. In conclusion, Gaulthorpe reflects on the wider implications for the research in terms of interdisciplinary collaboration.
So, perhaps the most innovative aspect of the device... is simply the revolution in creative process that it celebrates. A group of 'local’ thinkers have come to understand the value and kinship of interdisciplinary partnership...[12]

Fig. 3. Design for AegisHyposurface©. (Gaulthorpe, 2001)

The second example is a Masters design thesis project under my supervision, where the student was encouraged to publish the research. The project was documented with my editorial assistance and submitted to CAADRIA where it was rejected in the review process. Subsequently the same paper was submitted to eCAADe where it was accepted and presented [13]. The context in which this project was undertaken is the legacy of South Indian temple design. The carved temple walls developed by the people of the Hindu culture existed as a tool to document and dictate a way of living. Trying to reproduce the temple, in particular the intricately carved surfaces, requires the architectural skin to either lose fidelity through compromise in craft or require an enormous budget. The project proposed that by translating traditional handcraft ideologies to the digital medium of augmented reality, the traditional role of temple architecture could be realized in contemporary architecture. This proposition was explored through designs and technology mockups. From these designs the student reflected on the wider implications. He proposed the design precedent opens up a complimentary field of research within a cultural context, which can be considered as a form of cultural augmentation, to set a new agenda for mixed reality in architecture. Further reflection was undertaken on the range of ways in which AR had been conceived in the design: urban, building, wall and artefact. While the scalar strategy has been developed in relation to the traditional role of the temple, it was proposed that the design provides a basis for others to consider in terms
of the use of augmented reality as an active component of architecture. This was abstracted in terms of a diagram where augmentation can be considered as a continuum from the urban scale to that of an individual artefact.

The third example, taken from outside the CAAD community is a PhD by project, undertaken by Roland Snooks at RMIT University, which engages ‘with complex systems, generative design strategies and algorithmic techniques ... a process of embedding architectural design intention within generative algorithms[14].’

The designs embeds novel computational techniques that are captured by the phrase *Behavioural Formation*, the title of the thesis. While this is not an original concept, some of the tactics used by the candidate to intervene as a designer in the algorithmic process are. In particular the combination of explicit modelling and algorithmic procedures referred to as ‘strange feedback’ and ‘manifold swarms’. These and other strategies enable the candidate to imbue his architectural designs with a novel formal aesthetic. While the algorithms do not appear to be substantial, their application with an architectural design context is. In particular the candidate has contributed to discourse within a lineage of researchers who have explored generative algorithmic tactics based on the metaphor of the garden: John Frazerand his packet of seeds approach [15]; Richard Latham’s analogy of the designers as gardener, pruning and shaping form [16]; while Roland Snook’s tactics include the mechanism of the scaffold or trellis, around which generated form can coalesce. Snook’s research is
included in this discussion as an example of the sophisticated use of design computing within the current generation. This generation are typically not aware of the CAAD organizations, nor generally of the large body of design computing that, in effect, has underpinned their design explorations. While this ignorance of precedent breaks one of Tom Maver’s sins, the uninhibited tuning of algorithms in pursuit of a design agendas can, as evidenced by Snook’s projects, make a significant contribution to this legacy.

Fig. 6. Volatile formation (Snooks, 2012)

5 Concluding Remarks

This paper addresses an issue that has been omnipresent in the history of CAAD research: the tension between scientific method and the design discipline in which it operates. In Kvan’s elegant description of this dichotomy, he refers to the outcome of design computing as artefacts ‘expressible in the definitive and unambiguous clarity of data and procedures, to be evaluated in the integrity of their reasoning.’ The use of the word artefact is interesting, in that it is the same term used by many design researchers in the context of arguing that knowledge is embedded in the artefacts resulting from designing – drawings, models and ultimately buildings. The requirement for integrity and reasoning is also present and, as identified by Blythe, lies in the critical reflection that precedes, accompanies and follows the act of design. The examples briefly reviewed above illustrate how this reflection can be of value to
the agenda of CAAD research, beyond the individual design project or thesis. From a wider perspective, arguably, the establishment of CAAD was in response to issues that came from designing, in particular the complexity of large scale building with a high servicing component. This argument can be traced further back through the example of Mark Burry’s innovative research in realizing the Sagrada Familia. Without Gaudi’s 100 year old design Burry’s 1993 paper *The need to Step Beyond Conventional Architectural Software* [17] is unlikely to have been published, and with it a substantial body of research. The issues raised here are far more complex than presented, but it is hoped that this stimulates some reflection by the CAAD community on the potential of engaging with a new generation of designers who use computers as a research medium.

**References**

Development of a multi-disciplinary university wide design course

Bauke de Vries¹, Manon Grond¹ and Aant van der Zee¹

¹ Eindhoven University of Technology
{B.d.Vries,M.M.G.J.J.Grond,A.v.d.Zee}@tue.nl

Design is one of the basic skills of every engineer. However until now design is only seen as a core course in Architecture studies and lately in Industrial Engineering studies. This paper reports about the development of a design course for all departments of a typical technical university. After a short overview of design teaching tradition, an inventory is presented of the different interpretation of design by the various departments. The course development is presented over two periods: 2012-2014, and 2014-2015. In between a major change was conducted. The course learning goals and student evaluations are presented. In the discussion we reflect on fundamental and practical problems that occur in design teaching for such a wide audience. Finally we draw conclusions on the changing role of design what is needed to give design the same status as mathematics in a technical curriculum.

Keywords: Design, Design teaching, Multi-disciplinary design.

1 Introduction

University’s education is in constant change. Updating courses to cope with future needs and challenges is part of being an academic. Educational changes not only apply to the course content but less frequently also to the educational system. Educational systems are in return part of an even bigger societal system and based on education principles, which are also due to change. In Europe universities programs are harmonized according to the Bachelor (3 year)-Master (2 or 1 year) program structure since the Bologna declaration of 1999. This major change in Europe now starts to yield effect through an increasing mobility of students between European universities. However, the structure of Bachelor programs can differ significantly.

Another trend in European academic education that lasted many decades is the lack of appeal of technical studies. Many children that potentially were qualified to choose a technical study decided to go to another university (economic, managerial) because they felt that the provision at the other universities was better, namely after graduation a higher salary with less effort. Due to the economic crises in Europe since 2008
Development of a multi-disciplinary university wide design course

however, this trend has changed. Over the past two years the influx of students at technical universities has increased 10-20%.

In 2010 the Eindhoven University decided that a radical change was needed in their Bachelors program. Although the Eindhoven University’s education was ranked in par with the best in the world, there were two main reasons for a change: (1) The foreseen increasing need for engineers, and (2) the foreseen need of engineers with technical and non-technical expertise. The first ambition, namely to educate more engineers is closely related to the second one, namely to educate a new type of engineer. Until then, the Eindhoven University contained the traditional engineering studies (e.g. electrical engineering), the fundamental science studies (e.g. mathematics), the design studies (e.g. architecture) and the management studies (e.g. Industrial engineering). For today’s challenges however, an engineer needs knowledge and skill from a mix of these studies. Accordingly, the Bachelor program was restructured such that a student has much more freedom to choose courses from other studies than his/her major study. As a side effect it was anticipated that this program also will attract a wider variety of schoolchildren. Not only those that are interested in technical engineering, but also students who have an interest in human and management subjects.

An important part of the new Bachelor program was the establishment of five Basic courses that are compulsory for all students, regardless of which major study they are enrolled. The university board decided that the basic courses should reflect the basic skills of the future engineer. These five Basic courses are: Mathematics, Physics, Modelling, USE (User, Society and Enterprise) and Design. The first two courses come to no surprise, but the last three courses are new. The Modelling course aims at the conversion of technical design problems into forms that can be evaluated as mathematical expressions. The USE course aims at examining technological dilemmas from the perspective of humanities, history and ethics by questioning the role of the engineer. The Design course aims at learning design principles, processes, activities, and approaches by working on a design project.

The lead in the development of the new basic courses was allocated as follows: Modelling – departments of Industrial engineering & Innovation sciences and Mathematics & Computer science; USE – Industrial engineering & Innovation sciences; Design – departments of Built Environment and Industrial Design.

In this paper we focus on the development of the Basic Design course. In the first section we briefly discuss traditional methods in design teaching, followed by an overview of design perception and interpretation through different departments at a technical university. The course design section presents the considerations, implementation and evaluation of the first course that ran from study year 2012-2013 till 2013-2014 for an average number of 1200 students. The next section shows the changes that were made and the most recent experiences by the different groups of students in study year 2014-2015. In the discussion section many issues are discussed that we have experienced during the implementation and execution process. Finally, we draw conclusions with regard to the role of design in future academic teaching.
2 Design teaching

Teaching design has a long tradition in design studios. For many years architecture was the predominant design discipline in the academia. Architectural students are trained in a studio setting under supervision of a professional architect. Students work for one semester on a specific design subject. In the studio at the university campus students design is commented during the semester and at the end the complete design is presented and evaluated by the supervisors. Throughout the architectural study the design subject complexity will increase until the final graduation project. The teaching method follows closely the master-apprentice principle. Parallel to the design projects, courses are lectured on architectural theory and engineering. The knowledge gained in the courses support the design projects in the studios.

Relatively recent, industrial design has entered the academia. Industrial design has developed its own methods and techniques, but also embraced the design studio as the main environment for design teaching. In other engineering disciplines such as mechanical engineering and electrical engineering, design is seen as part of the engineering process and not as a core skill. Computer aided design has not effected design education substantially. CAD training is often only a side track of the studio work and CAD skills are learned by doing.

In contrast with the Basic courses Mathematics and Physics, there are no teaching handbooks for design on the academic level. Architectural design books are mostly only presenting architecture, but hardly any insight on the design process. Many well knowns researchers like Bryan Lawson [1] and Donald Schön [2] have researched design cognition and thereby also touched upon design training. Other researchers have proposed methods to capture the complexity of the architectural design process (John Habraken, Herbert Simon, Christopher Alexander). Design methods have raised fundamental discussions amongst academics and between academics and architects. Design methods were often not widely adopted in architectural practice, but only seen as a scientific abstraction. That is most likely one of the main reasons why architectural design handbooks do not exist. Industrial design has brought forward a number of influential books in the industrial design process [3] and design teaching [4]. Industrial design as an academic discipline is developing itself more rapidly than architecture with its traditional roots. Last but not least there exist many books on engineering design with a basis in mechanical engineering. These books show remarkably resemblance which shows that in this field there is a strong common understanding on what engineering design is and how this should be taught (see e.g. [5]).

In scientific journals like Design Studies, European Journal of Engineering education, International Journal of Technology and Design education many papers are published on the effect of different course structures on students’ design performance (see e.g. [6], [7], [8], [9]). However these studies focus on a single discipline (e.g. architecture) or on multi-disciplinary design, but only within the boundaries of one department or one major study.

Design has a very broad meaning inside and outside a technical university. For our university we agreed upon the following definition for a design artefact:
• Physical product, like a building or coffee machine
• A system, like a software system or an organization
• A service, like a customer service or a public service

Even then, the interpretation of what design is amongst the different departments is diverse. Below a brief description is presented for each department in alphabetical order:

**Applied physics:** Design is not a special topic in the applied physics curriculum. Physicists do design experimental setups but these are usually not considered an end product.

**Biomedical engineering:** Biomedical engineering is built upon other departments and therefore not discussed separately here.

**Built environment:** Design is core for the whole curriculum and has a focus on spatial design ranging from building components to landscape.

**Chemical engineering and chemistry:** In chemical engineering design refers to design of chemical processes and its installations.

**Electrical engineering:** Design of electric circuits and automation system is a core component.

**Industrial design:** Design is core for the whole curriculum and has a focus on user experiences of the design artefact.

**Industrial engineering and Innovation sciences:** Design of services and organizations is recognized as a design process.

**Mathematics and Computer science:** In computer science software design is a core topic supported by well-founded methods and techniques.

**Mechanical engineering:** Engineering design has its basis in mechanical engineering and has a focus on the assembly of parts.

From the short descriptions we can conclude that different interpretation exists with regard to design phenomenon, namely:

• **Design as a product or as a process**
  Although for some departments, design of a product, system or service might not be a major topic, nevertheless design as a process occurs everywhere.

• **Design at different levels of scale**
  Design ranges from quantum physics level to regional planning level. Multi-level design and engineering is still quite rare.

• **Design at different levels of abstraction**
  Product design results in tangible products, whereas system design and service design are not tangible, but will become so after implementation.

• **Design as a deterministic or a non-deterministic process**
  For some departments design is an open ended, creative process, whereas for others design is a closed, solution oriented process.

In the following two sections we describe the design and evaluation of the basic design course of two episodes that subsequently ran over the study years 2012-2013 till 2013-2014, and 2014-2015. The first episode was focused on design theory, and the second episode was focused on design skill. The descriptions are kept relatively
brief using factual data, while in the discussion section we present our personal observations based upon discussions with students and teachers.

3 Course design: Theory-based

The learning objectives of course the in the first episode were defined in three components:

1. Knowledge component. Students:
   • gain knowledge about and see relationships between design principles, skills, approaches, context and quality, including different perspectives on design;
   • learn the (variety of) vocabulary within design to enable communicating within the own discipline and between disciplines;

2. Skill component. Students acquire design skills to:
   • generate ideas and concepts based on previous findings and objectives;
   • evaluate a design in various stages of the design process;
   • learn to reflect in and on own design actions and process;

3. Attitude component. Students show:
   • inventiveness: the designer questions and open ups the situation at hand in the move towards a design solution
   • openness and receptivity towards other than one's own discipline

The course consisted of two parallel tracks running over eight weeks, namely one track of weekly lectures with accompanying assignments and one track of working on a design assignment. The weekly lectures covered the following design topics:

- Design in a nutshell
- Design specification
- Design methods and techniques
- Design evaluation
- Design visualization & representation
- Design management and business

In the first week’s assignment students were asked to write down a design need or challenge. In the following weeks new design methods and techniques were introduced in the lectures. In the weekly assignment they reflected upon a chosen methods or technique for their need/challenge. The weekly assignments were peer-reviewed by three fellow students. The lectures were supported by slides and a thesaurus containing design terminology with its definitions.

Parallel to the weekly assignments, students worked on a design assignment. Therefore they could choose from three different types of assignments

- High Tech Systems
- Integral design
- Social innovation design

The assignments were all aiming at a product, but they differed in scale, abstraction, process, and group size. In the High Tech Systems project a wave stepper robot was designed in groups of two students using SysML modelling language and
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In the Integral design project students worked individually on low-carbon building using 3D modelling and energy simulation tools. In the Social innovation design project, students worked in teams on innovations that promote human health. The design projects were concluded with a general meeting of all students with a contest for the best design of the year.

The most important outcomes of the questionnaire that was sent to the students shortly after the end of the semester are:

1. Discrepancy between theory and project
2. Relevance for study not recognized
3. Peer review not appreciated

Students felt that only a small part of what was learned in the lectures could be applied in the design project. They did not see the relationship between the design methods and techniques and the design assignment. Large groups of students especially from those departments where design is not a major topic considered the course ‘a waste of time’, because it did not contribute to their education. Finally the peer-reviewing system was not highly valued especially not by the strong students because they received only poor comments.

4 Course re-design: Skill-based

The learning objectives in the second episode of the basic design course are divided into:

1. Individual learning objectives
   - Set and accomplish a measurable and/or experienceable individual design goal;
   - Use specific design methodologies in a project and develop his/her own view of the merits of this methodology;
   - Show an attitude of inventiveness, dare and responsibility towards his/her design part/aspect;
   - Show openness towards integration of design parts/aspect from another than his/her own discipline.

2. Team learning objectives
   - Set and accomplish a measurable and/or experienceable team design goal;
   - Reflect upon various views of and methodologies for designing that are typical for the engineering professions in a design team;
   - Communicate the design and design process using the general design vocabulary from the thesaurus;
   - Integrate different design parts/aspects in the group process/design.

Because the overall student evaluation of the initial Basic Design course was poor and below the university’s standard, a major change was deemed necessary. The educational programs directors of the departments concluded that that course should
be based on the well-known design driven education paradigm. Essential in this paradigm is working in multi-disciplinary design teams under supervision of a tutor.

Consequently the course was restructured as follows. Students are allocated in teams of five students, ideally all from different departments. In the first week there is a general introduction to the course and the team specifies the design subject together with their tutor. In week 2 and 3 students follow one of the following workshops: (1) Ideation & visualization interactions, (2) Systems engineering, (3) Spatial design and energy performance, (4) Design prototyping. Ideally students from one team follow different workshops. From week 4 onwards, the students work as a team on their design subject using the knowledge from the workshops. A study guide describes the weekly deliverables for the team as a whole and for the student as an individual. At the end of the semester a team design report is submitted and an individual report on the his/her own design part/aspect and design process. In a final general lecture the best design was selected from all student teams.

The most important outcomes of this year’s (2015) questionnaire is:
1. Students appreciated working in multi-disciplinary teams
2. The workshops sometimes did not match with the chosen design subject
3. The weekly program was either too vague or too strict

Students appreciated the opportunity to meet and work with students from other departments. The workshop skills were not always applicable to the design subject chosen in the first week. The problem was caused by a difference in scale and abstraction. Differences in attitude between students caused difficulties in the design process. Designerly oriented students prefer an open, creative process, whereas fundamental science students are frustrated about the vagueness of what is expected from them.

5 Discussion

During the development of the course and while running the course many issues were discussed between the responsible departments and between teachers and students. First we will discuss the more fundamental issues and then the practical issues.

Fundamental

There is no common understanding about design nor design teaching. The fundamental differences between the departments presented above were apparent right from the start. Therefore it was decided that students should be confronted with multiple design approaches, instead of a single generic approach. The downside of this standpoint is that it is almost impossible to structure the course. In the first episode of the course students complained that the lectures did not synchronize with the design projects. Design theory was learned too late or was not applicable at all. In the second episode a very basic structure was implied namely: specification, concepts, evaluation, refinement, finalization and presentation. Dependent on the tutors background (i.e. the department that he/she was recruited from), this basic structure was followed or neglected, leading to confusion among the students.
In both episodes teaching design methods and techniques is part of the course. In the first episode this was established through lectures, in the second episode through workshops. One could argue to implement the complete course as a design studio with tutoring and no class room teaching. However, most departments feel that students in their bachelors don’t have enough expertise to substantially contribute to a design project. On top of that, even now groups of students complain that they ‘did not learn a lot’. Technical students’ cognitive talents are not well enough challenged in a design project. A tutor could take care of the design knowledge transfer, but whereas we concluded that there is no common understanding about design this applies also to tutors.

Multi-disciplinarity can be implemented in the course in different ways. In the first episode students from different departments subscribed to of the three assignment types. Every student followed the design approach that fitted that assignment type. The High Tech Systems assignment was highly structured while the Social innovation design assignment was very explorative, and the Integral design assignment was in between. Collaboration between students was sometimes promoted but not always. In the second episode students worked in teams stemming from different departments. Moreover they followed different workshops and they were requested to apply the workshop skills in the team project. In the latter situation the tutor plays an important role in finding a design subject that allows every student to use his/her workshop skills. Due to differences in scale and abstraction between the workshop this turned out pretty hard sometimes.

Groups of students debated the relevance of the design course for their major study. An easy solution to this problem is to have every student follow a workshop that is offered by their own department. As a consequence the problem of integrating different workshops into one design will become even harder. One step further every student follows the complete course in his/her own department with teachers and a topic that are familiar. In that case one could argue that course does not deserve the name Basic course anymore, because every department is teaching its own design course without any common part.

Groups of students requested a course structure, results and grading that leaves no room for ambiguity. This request is in sharp conflict with the nature of design. In principle a course could be designed such that all students work on the same assignment, following the same instructions, resulting in the same design. Even though these groups of students would probably appreciate this course structure, the responsible teachers feel that challenging especially these students to step out of their comfort zone, is one of the most important objectives of this course. Thus ambiguity should be part of a design course despite the frustration that it causes.

Practical
Teaching approximately 1200 students is a logistical challenge. The largest class room at the TU/e has 300 seats and for the design studios a lot of floor space is needed. The administration of students, student teams, workshop and the room scheduling demands much labor. The distribution of course material and submission of reports requires robust automation systems. The upscaling from courses that would
fit in one class room to courses with 12 students put a lot of stress on personnel and facilities. To overcome some of these issues the following measures were taken.

The lectures that were given in parallel class rooms linked through video connections in the first episode were largely skipped in the second. Students stayed away from these lectures and instead watched the video recordings. In the last episode of the course only the first and the last lectures are general and compulsory for all students. The other lectures about design methods and techniques were recorded as web lectures of 5-10 minutes. Students can watch these web lectures as input to the design project.

Students turn out to be very sensitive to course organization. This applies to the structure as well as to the technology. If course information is not easily accessible or even worse not clear, then frustration arises quickly. Even so, if systems fail or give unexpected messages, then students’ tolerance is low. Although these matters of course should not hinder a student in his/her work, sometimes problems are simply out of control of a teacher. Evaluations however show that these frustrations have a high impact on the overall appreciation of a course.

The peer-reviewing procedure worked relatively well technically but was not highly appreciated by the students. To ensure consistency and prevent abuse, a sample of all reviews and scores by fellow students was checked by teachers. The students’ reviews and scores turned out to be very consistent with the teacher’s scores. However, especially the strong students were unhappy with the peer-reviewing. They were disappointed by the reviews they received because on average they were below their own standard. In general students like teamwork but they don’t like they idea of learning from each other. They came to the university to learn and receive feedback from scientists. In the workshop in-depth design knowledge is conveyed by staff members and can be tested through assignments. In the design project for practical reasons we involved student assistants that have less design experience. Even more important, students desire clear cut criteria for evaluation of their work what is in conflict with the open-ended nature of a design project.

6 Conclusion

The main conclusion at this time is, that design as a core skill for a Technical University Master is not yet recognized by all students. A comparison with the Basic Mathematics course (Calculus) can illustrate this. A student from the department of the Built Environment will never question why he/she should follow a Basic course Mathematics. Before coming to the technical university he/she knew that this is part of the education. In contrast many mathematics students question why they should follow a Basic course Design. For them a design course comes as a surprise, and they cannot understand the added value for their education.

Insisting on the idea that design is something that is behold by the creative genius will isolate the designers from the engineering disciplines. Instead design serves as an integrator between disciplines. A uniform language is needed that allows designers and engineers to communicate. Intriguing in that regard is the development of a
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relatively young discipline of Computing Science. In a few years a standard language (UML) and an standard book with code samples [10] was developed that is accepted widely in science and practice. Interestingly many of the terms were adapted from architecture, such as system architecture and design patterns. Due to the mathematical background of many software scientists, this field succeeded in explicating their knowledge in a uniform interpretable way. Similar steps are needed for expressing design concepts and communication between engineering disciplines.

On top a uniform design language, uniform criteria for design evaluation are needed. These are a combination of qualitative and quantitative criteria, dependent on the design subject. Interestingly, this demand for evaluation of design and design alternatives is also expressed by professional clients in design and engineering practice. In education the tradition still holds that we should not limit our students’ creativity with the technical and financial constraints of today. This approach seems not realistic anymore. Design is a constant process of decision-making. Only if we demand explicit decision-making by students in their design project and by teachers (or tutors) in their evaluation, then discussions about design quality becomes manageable. Today in education we observe that the use of rubrics for evaluation of work becomes a standard technique that also will objectify design quality.

Design is not anymore the privilege of only a few departments of a technical university, but it will become as basic and as normal as mathematics or physics to any technical student. Design can only deserve that position if it explicates itself in a formal way and if it is recognized by all disciplines as essential for complex engineering tasks.

References

CAAD conferences
A brief history

Gabriela Celani\(^1\) and Pedro Veloso\(^2\)

\(^1\)University of Campinas
celani@fec.unicamp.br

\(^2\)Carnegie Mellon University
pveloso@andrew.cmu.edu

Abstract. This paper analyzes the evolution and trends of international conferences addressing Computer-Aided Architectural Design over the past five decades. It starts with the Design Methods Movement conferences, when the possible contributions of computers to Architectural Design started being discussed. It shows how new interests along the history of CAAD development motivated the appearance of conferences on specific topics, and it ends identifying a recent interest towards architectural practice and the software development. With this work we expect to contribute to an “archaeology” of CAAD studies.

Keywords: CAAD conferences, archaeology of CAAD.

1 Introduction

Although closely related, the acronyms CAD and CAAD originally refered to completely different things. While the term Computer-Aided Design was related to vector-based graphic software for drafting, as defined by the industry, Computer-Aided Architectural Design has been used to describe a wide area of research, ranging from very abstract computational thinking about architecture to more concrete computer implementations and automated fabrication.

In the late 1980s, Mitchell [1] blamed simplified CAD software, especially created for personal computers in the 1970s, for a deviation in CAAD development. Later on, Burry [2] blamed the similarity between the two acronyms for the marginal place that CAAD has occupied in the architectural curriculum. Still according to him, the emphasis has been on using CAD software for increasing efficiency in architectural firms, over the “quest for design excellence in itself”, which was one of the original objectives of CAAD.

But these two acronyms, as we will see at the end of this paper, are not so distant any more, thanks to a closer collaboration between architects, researchers and software developers nowadays. This is, to a large extent, the result of the
dissemination of the research in the field, propitiated by the conferences that we will describe in the next sessions.

Since the 1960’s, conferences related to CAAD started being organized in different countries, involving people from universities, the industry and the architectural practice. Some of these conference series formed regional networks and even global networks, through associations, online databases and journals.

Hoping to contribute to the understanding of this merging between CAAD and CAD, and in order to stress the former’s specificities and development, this paper analyzes the evolution and trends of international conferences addressing Computer-Aided Architectural Design over the past five decades. It starts with the Design Methods Movement, when the possible contributions of computers to Architectural Design started being discussed, and ends with robots, one of the latest trends in high tech Architecture.

The motivation for writing this paper was the lack of knowledge that most young attendants have about the origins of these conferences and how they relate to each other. This information can be very useful for helping them engage in this now well-established network of researchers.

This study did not consider conferences on Geographic Information Systems (GIS), because although these systems are very used in the Architectural Design process, these conferences usually focus on city and regional planning, falling outside the scope of the present research. Computer Graphics Conferences, such as SIGGraph, which started as early as 1974, were also not included, because they focus mainly on the technical, not the cognitive aspects of the use of the computer for Architectural Design. Moreover, although we acknowledge the importance of local conferences, we only considered the international ones held in English, due to language constraints and because those probably represent international trends better.

2 The origins

The origins of CAAD development are closely related to the Design Methods Movement of the 1960’s, which begun with the first Conference on Design Methods held in London, in 1962. It consisted of a series of conferences and publications, and its main goals were (1) to design better, by understanding the design process, (2) to externalize the design process, allowing large teams to collaborate from the early stages and reaching a higher level of complexity, and (3) to use the computer to automate repetitive parts of the design process [3].

According to Cross [4], “the 1960s (...) saw the beginnings of computer programs for problem solving” (p.1). One of the first layout optimization programs was developed by Mosley [5]. By the end of the 1960s, and the beginning of the 1970s CAAD was already established. According to Bayazit [6],

“Beginning in the 1970s, computer scientists became interested in systematic design methods and design science. They were trying to program and evaluate building performance to justify scientific design decisions. At the National Bureau of Standards in the U.S., the first International Congress on Performance Concept in
Building was organized in 1972. It brought a new perspective to design research in architecture. Thomas A. Markus and Thomas Maver had been working on building performance at Strathclyde University. Thomas Maver, a computer-aided design programmer, started to work on the programming of environmental building performance evaluation programs. Also, Peter Cowan established the building research center at the University of Sydney in Australia”. (p.25)

Other centers were the interaction between design science and CAD was occurring were Carnegie Mellon University (with Herbert Simon and Alan Newell), the University of California at Berkeley (with Horst Rittel and Christopher Alexander), the University of California at Los Angeles (with Bill Mitchell and George Stiny), MIT (with Nicholas Negroponte) and others (see [7]).

A new interest in design methods by computer scientists reappeared in the 1980’s, at stated by Cross [8]:

“There was also a broader renewal of interest in design methodology in the late 1980s – especially in AI developments, where hope springs again for design automation and/or intelligent electronic design assistants.” (p.17)

...and by Bayazit [6]:

“Studies on AI researchers affected the development of studies on designers, as experts. “Think-aloud” techniques and “protocol analysis” were adopted by designers”. (p.27)

The relation between computers and design methods was the main focus of a workshop held in 1964 in Atlantic City, USA, titled The First Annual Design Automation Workshop. The Workshop became the Design Automation Conference (DAC) series, which has been held every year since then, for more than 50 years. Although nowadays it is concerned mainly with automated methods for Electrical Engineering Design, in the lack of other conferences, DAC served also as a forum for the early CAAD researchers, especially during the 1970’s, as stated by Joyner [9]:

“Indeed, through the 1970s, papers from architectural, mechanical and other areas of design automation appeared at DAC”. (p.28)

In the 1971 conference, for example, both William Mitchell and Charles Eastman presented papers, titled respectively “The Automated Generation of Architectural Form” and “GSP: A System for Computer Assisted Space Planning”. However, after the 1970s, DAC stopped being a strictly technical conference and started including a large trade show, which eventually became the main focus of the event [9]. Only topics concerned with automated electronic design were included in the conference, but new forums for discussing computer-aided architectural design were created, as we will see in the next sessions.

In the early 1980s, researchers developing CAAD applications felt the need to create their own forums for discussions, where both architectural design and computer
issues could be addressed together. Although independent, these new organizations were closely connected to Universities, to ensure the academic character of the discussions. Koutamanis [10] sees this moment as “the period when CAAD became a recognizable area” and increased its “scientific significance” (p.629). As a result, in the 1990s “CAAD is an established area, with its own conferences, journals and almost exclusive rights (...) to an expensive and promising technology” (p.634).

3 The sister organizations

Since the 1980s, international organizations were created in each continent, to support regional academic discussions about CAAD research and development. The first of such organizations, the Association for CAD in Architecture (ACADIA), was founded in North America in 1981 “by some of the pioneers in the field of design computation, including Bill Mitchell, Chuck Eastman, and Chris Yessios” [11]. Its mission is to “facilitate critical investigations into the role of computation in architecture, planning, and building science, encouraging innovation in design creativity, sustainability, and education” (ibid.). ACADIA has been held in different cities of the United States and Canada.

Education and research in Computer Aided Architectural Design in Europe (eCAADe) was the second organization to appear, founded in Europe in 1983, including a new focus on education. It is described as an

“association of institutions and individuals with a common interest in promoting good practice and sharing information in relation to the use of computers in research and education in architecture and related professions.” [12]

In 1985, CAAD Futures was founded in the Netherlands, “with the purpose of promoting, through international conferences and publications, the advancement of Computer Aided Architectural Design in the service of those concerned with the quality of the built environment” (ibid.). In the Introduction to the Proceedings of the first Conference, Alan Pipes [13] described the founders of CAAD Futures as “veterans of a hundred and one CAD conferences” who were “bemoaning the degree to which big business was taking over the conference scene (...) selling was replacing thinking, products were replacing ideas” ([13], p.18). Differently from the other sister organizations, which are always held in the same continent or region, since its foundation, CAAD Futures has been held in Europe, North America, Asia and, for the first time, will be held in South America in 2015.

Only a decade later similar organizations appeared in the other continents. The Association for CAAD Research in Asia (CAADRIA) was founded in 1996, and the Sociedad Iberoamericana de Gráfica Digital (SIGraDi) was created one year later, in 1997. The Arab Society for CAAD (ASCAAD) was only created in 2001, covering Northern Africa and the Middle East.

The six organizations have annual conferences (except for CAAD Futures, which is biannual, and for ASCAAD, which has had problems due to the political situation
of its region), and share similar goals of supporting CAAD research, teaching and development. SIGraDi is the only one that uses three different languages (Spanish, Portuguese and English), while all the others use only English as their official language. SIGraDi’s conferences also have a broader scope, including areas such as industrial design and media arts, which is probably related to the relative isolation of the South American continent in relation to the main centers where CAAD has traditionally been researched, a situation that is changing quickly in recent years. Figure 1 shows the geographic distribution of the sister organizations’ conferences, and Figure 2 shows their timeline.

![Geographic distribution of the sister organizations’ conferences.](https://www.google.com/maps/d/edit?mid=zHVI6zCSeA0M.k1d3jUr43TPI)

![Timeline of the sister organizations’ conferences.](https://www.google.com/maps/d/edit?mid=zHVI6zCSeA0M.k1d3jUr43TPI)

### 3.1 CuminCAD

In 1998 CuminCAD, the CUMulative INdex of papers on CAD, was established by Bob Martens (TU Vienna) and Ziga Turk (University of Ljubljana), funded by the
European Commission, as a “response to limited, difficult access to scientific information in the field of CAAD” ([15] p.221). It inherited approximately 1000 entries from another CAAD database that had been previously created by Yehuda Kalay, CADLine.

Among all CAAD conferences, CAAD Futures was the only one that had its Proceedings published by a renowned publishing house (at a high purchasing cost), while the other conferences’ books, with a limited number of copies, were in risk of becoming just “gray literature” (ibid., p.221). Therefore, this online database started publishing CAAD conferences papers and became an important resource for doctoral students and young researchers in the field.

At http://cumincad.architexturez.net/ one can see the metadata of papers and download most of the full papers or complete proceedings of the sister organizations’ conferences plus those of

- DDSS - Design & Decision Support Systems in Architecture and Urban Planning, a series of conferences organized bi-annually by Eindhoven University of Technology (since 1992);
- AK-AI – a series of conferences organized by Arbeitskreis Architekturinformatik, a German working group on Computer Science applied to Architecture (since 1993);
- EAEA - European Architectural Envisioning Association (since 1993)

The metadata of all papers published on IJAC, the International Journal of Architectural Computing, are also listed, and full papers from 2003 to 2009 can be downloaded. At http://cumincad.scix.net/cgi-bin/works it is possible to perform searches and browse the papers by series.

CumincAD is presently being supported by the sister organizations, and its access requires subscription, but is free, during one year, to attendants of their conferences. At the end of 2015, the sister organizations plan to make a larger investment in CumincAD, in order to upgrade its equipment and management system, and turn it into an open access database.

The number of entries presently found at CumincAD for conference and journal papers is shown on Table 1. Reports and theses are also available. One interesting thing about this comprehensive database is the possibility to perform thorough searches. For example, Figure 3 shows the most frequent keywords found in CumincAD’s keyword index, not considering common words such as “architecture”, “urban”, “city”, “construction”, “system” and “graphic”.
Table 1. Entries presently found at CuminCAD. (Source: http://cumincad.scix.net)

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<th>Sister organizations</th>
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<td>ACADIA</td>
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<td>Journal papers</td>
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<td>SIGRADE</td>
<td>Others ~</td>
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*Number of conferences, not papers.

Fig. 3. Most frequent keywords found in CuminCAD’s keyword index. (Source: http://cumincad.scix.net/cgi-bin/work/BrowseAZ?name=titles)

3.2 Architectural Computing

In 2003 the Architectural Computing alliance was created by Andre Brown, from the University of Liverpool. It consisted simply of a website (with links to the regional organizations (http://www.architecturalcomputing.org/) firstly ACADIA, eCAADe, CAADRIA, SIGraDi and CAAD Futures, and later ASCAAD), but it helped strengthening the relations between them. Nowadays, each organization’s website has a link to “related organizations”, expanding the capillarity. Architectural Computing supports the International Journal of Architectural Computing (IJAC), and it can be compared to the International Building Performance Simulation Association.
CAAD conferences - A brief history

(http://www.ibpsa.org), which supports its international conferences and a scientific journal in the field.

3.3 IJAC

In 2003 the International Journal of Architectural Computing (IJAC) was founded by eCAADe, ACADIA, SIGraDi and CAADRIA, with CAAD Futures’ support. This peer-reviewed journal is published by Multi-Science and has Andre Brown as editor-in-chief. The journal publishes four issues every year, each of which is supervised by an editorial committee from each of the founding organizations. Instructions for authors can be found at http://www.multi-science.co.uk/ijac.htm, and the access to content can be done through http://www.metapress.com/content/121497/.

The organization of these international conferences in every continent, and the creation of an online database and a scientific journal resulted in the consolidation of the field, supporting the introduction of CAAD in Architecture Schools all over the world.

4 John Gero’s conferences

The story of CAAD conferences would be incomplete without a proper reference to John Gero’s conferences. Differently from the sister organizations’ conferences, which had a broader scope, the conference series created by Gero targeted more specific issues, fostering a deeper discussion on special aspects of CAAD. With the purpose of developing a community of researchers, establishing a rigorous scientific style that would give respectability to this new field, Gero created six different series of conferences, following each decade’s main trends.

In the mid 1980s he started two conference series, one on Design Methods for CAD and another one on Artificial Intelligence in Design (AID). The first consisted of only four conferences (1985, 1992, 1995, 1997) because its topic ended up being absorbed by the AID conferences. The AID series targeted the application of Artificial Intelligence techniques in design research:

“The first two conferences used the names of the dominant paradigms of their time [Knowledge Engineering and Expert Systems]. However, I moved to bring all of this work under the umbrella title of “Artificial Intelligence”, and the Artificial Intelligence in Design label was used”. [15]

In 2004, the name of this series changed to accommodate new interests. According to Gero [15], in the 1990s the interest in cognitive studies increased and he saw an opportunity to link artificial intelligence and cognitive science simultaneously to design research. For this reason, the AID conference series had its title and scope changed, and became Design Computing and Cognition. But, as Gero puts it, DCC can be considered a “direct outgrowth of the AID series”, and the 7th DCC conference
can be considered the 17th conference of a series that started thirty years ago, with KE’85[15].

From 1999 to 2004 Gero also ran the Visual and Spatial Reasoning in Design conference series, with only three events, in order to "explore this is a separate, specialized topic within design research". However, this separate issue also ended being absorbed by the DCC conferences, and the series was discontinued. Similarly, the workshop on Agents in Design in 2002 “aimed to bring this research area to the attention of design researchers and to bring researchers in this topic together”, but it also ended being merged with the DCC conference (Figure 4).

Gero also hosted, with Mary Lou Maher, the Design Creativity Conference series from 1989 to 2005, and three Studying Designers conferences, plus a number of separate ones.

![Fig.4. Timeline of Gero’s conferences.](http://mason.gmu.edu/~jgero/conferences.htm)

Most of Gero’s conferences were held in Sydney and were linked to his Key Centre for Design Computing. They propitiated the participation of many PhD students from that side of the world, contributing to the formation of a whole generation of scientifically sound CAAD researchers.

5 Other conferences

There are still many other conferences related to CAAD that are worth mentioning, some of which also have papers or abstracts published at Cumincad:

- Building Simulation Conference (since 1985)
- Conference on Design Theory and Methodology (since 1988)
- Design Thinking Research Symposia (since 1992)
- Nexus Architecture and Mathematics Conference (since 1996)
- Mathematics and Design (since 1997)
- Smart Geometry (since 2003)
- Advances in Architectural Geometry (since 2008)
- SimAUD-Symposium on Simulation for Arch. & Urban Design (since 2010)
- Algode-Algorithmic Design for Architecture and Urban Design (since 2011)
- Rob Arch - Robotic Fabrication in Architecture, Art & Design (since 2012)
BIM Conference (since 2013)

Each of them has been created to bring attention and promote discussion on the most relevant topics that have been introduced to the area in the past years, fostering research and supporting teaching in each field. Their chronology of appearance tells us a lot about which were the hot issues and technical novelties in every decade. Some of the most recently created have introduced innovative formats. For example, instead of presenting papers, Smart Geometry attendants are invited to engage on workshops in which the conference topics are experienced in practice.

It is also noteworthy that some of the conferences created more recently, namely Smart Geometry and Architectural Geometry, have strong connections to the architectural practice in their origins and aim at impacting the CAAD software industry, instead of influencing only researchers. Smart Geometry, for example, was founded in 2001 as a discussion group by architects Hugh Whitehead, Lars Hesselgren and J. Parrish, with collaborators Robert Aish, Robert Woodburry, Axel Kilian, Mark Burry and Chris Williams, “as a way to recapture parametric and computational design to architecture” ([16] p.8). The first conferences had a focus on “software development, new tools for architects and engaging with ideas outside the boundaries of ‘architecture’” ([16] p.8), and resulted in the development of Generative Components. The idea was to create an environment for explorations, away from both the architectural office and the university.

Architectural Geometry describes itself as a conference for “connecting researchers from architectural and engineering practices, academia and industry (…) supported by the direct participation of the most renowned architectural design and engineering offices along with academic laboratories”. [17]

In other words, if the first CAAD conferences were looking at academia as a fertile ground for innovation, now the opposite seems to occur. Advanced practices bring in their daily problems and the CAAD software and hardware industries see this as an opportunity to develop new products, from parametric modeling and BIM packages to 3D printers and manufacturing robots, which, in turn, end up influencing education.

6 Discussion

This paper presented an overview of the main international CAAD conferences created since the 1980s, stressing their importance in establishing CAAD as a scientific field of research. It is also important to acknowledge the existence of many local conference series on similar topics, most of them held in local languages, which had also a great impact in the field. For example, in the 1990s, a series of National Seminars on the Teaching of Applied Informatics were held in Brazil, in Portuguese, which had an important influence in the introduction of CAAD subjects in the architectural curriculum.

The diversity of interests and contexts that characterize current conferences makes it difficult to select predominant topics. However, in comparison to the background in
which the CAAD conferences emerged, it is possible to detect some structural changes.

In the 1960s most of the researches in the domain of the DMM were interested in developing a science of design, focusing on rational methods that allowed to externalize and even compute the design process – what J. C. Jones [18] called glass-box methods in opposition to designer-centered black-box methods. CAAD researches distinguished themselves from the drafting interest in which CAD industry orbited around for a long time. Instead of dealing with automating conventional tools or accelerating current practices, CAAD research assumed that computation implied a rupture in the modus operandi of architectural design. Therefore, they investigated computational techniques to solve general design problems or even to deal with design automation.

In the last three decades, globalization process and the end of ideological polarization gave way to a leap towards a pragmatism in architectural design and theory [19]. This general leap in architecture accompanied not only radical changes in CAD industry but also in CAAD research.

In the late 1980s and 1990s, there was a wide interest in experimental architecture to challenge the conventional geometry. Animation and 3d-modelling software became a gateway for different types of computational geometries and algorithms in design practice. Simulation, digital fabrication and - more recently - robots made these new formal experiments feasible. In the 2000s, Scripting and parametric-modelling became a platform to explicitly orchestrate design flow of information, while BIM expanded the framework of representation of the buildings beyond geometry to incorporate AEC data.

This series of changes reinforces the idea that “the focal point for advanced technologies in architectural design has shifted from the outer edges of the virtual to a position of hybridity of the actual” [20], which, in the case CAAD, seems to characterize a pragmatic turn. Topics that were part of CAAD research for decades, such as an information models or generative design, came to the forefront of the industry. Knowledge from other fields and technical novelties from different industries are often and quickly incorporated in CAAD as conference topics. Practitioners and researchers related to CAAD develop specific algorithms to fulfill their own design needs and sometimes they even change the industry – in other words: they build their own tools (Aish in [16]). This means that the words CAD and CAAD, as described at the beginning of this paper, are becoming less different, as a feedback between practice, industry and academia is becoming more frequent.

As we stated above, CAAD was a research area inquiring primarily into computational solutions for general design problems or even to contribute to a general science of design. While the operative optimism of the pioneers remains, an intense feedback between research, practice and the industry seems to predate any generalizable model or method developed only in one of these fields. In this context, CAAD conferences become an experimental territory to contribute to on-going architectural design changes. So, in order to better understand tendencies and predict future developments, a constant work needs to be done in this archeology of CAAD Conferences.
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Modeling, analyzing and simulating the city
Abstract. This paper presents an experiment on an open source construction system named Woka, which allows anyone to design and produce dwellings using standard CNC techniques. Woka was developed as a dialogical design process that empowers self-builders to act in a more autonomous way, expanding the traditional role of design practice and the way buildings are created. The advent and popularization of new design and fabrication processes have encouraged a flux of new theories and project strategies based on computing, each with its promise of changing the architectural practice. Some of these resulted in intellectually seductive; visually provocative and complex shaped architectures, generating a new formal repertoire, but doesn’t indicate a paradigm shift in the process of production of architectural space, still based on authorship. Woka challenges this traditional process proposing dialogue as a design approach, shifting the focus from the object to intersubjectivity, amplifying the potential for novelty to arise.

Keywords: Parametric design, digital fabrication, dialogical design, autonomous building

1 Introduction

The name Woka derives from the wiki (open to) and oca (indigenous house or dwelling). It is an open construction system that updates the building tradition of indigenous people where residents design and build their own homes. Based on a DIY (Do it Yourself) logic, it is a process that allows anyone to design, download, print, build and complete their house or components. Woka explores the integration between Wikihouse, Sketchup (dynamic components) and Bimbon as an interface that mediates the design and building process of the house. Woka explores the potential of parametric design to involve the user in the design process. In traditional design processes – that use CAD programs as an extension of the drawing board – the change of parameters, like the geometry of a room, could only be implemented by suppression and reconstruction. This is rethought in a parametric process, where the model can be defined as a set of geometric relationships that are applied through
Towards a dialogical design of future cities

parametric expressions and constraints. This chain of geometrical relations can be manipulated without losing the consistency of the hole. If these parameters can be manipulated in a dynamic form this opens the possibility to involve the user in the design process.

It is because the digital representation is constructed with codes and algorithms that can be read by numerically controlled machines, that the information embedded in the drawings can be directly materialized by CNC laser cutters, CNC milling, 3D printing etc. This ability to generate constructive information directly from the drawings information is one of the most relevant aspects in contemporary architecture. This direct connection between design and fabrication is already a common process in automotive, aerospace and shipbuilding industries. However, it was only in the last decades that the advances in computer aided design (CAD) and computer aided manufacturing (CAM) has caused more impact in architectural production.

The possibility to alter parameters in real time in architectural representation already existed at the first stages of development of digital design technologies. Ivan Sutherland Sketchpad System for example enabled the user to change the drawing without breaking the chain of geometrical relationships. This was later further developed in software like Radar CH, created in Budapest by Gábor Bojár in 1982, latter known as ArchiCAD and the first BIM software made available on a personal computer, or REVIT, one of the most popular BIM software that was conceived by Parametric Technology Corporation (PTC) and later purchased by Autodesk. Although these software’s made important advances they were built based on standard building workflows and normally don’t leave much space to different approaches to design. Most software developers were more focused on the improvement in productivity and the automation of tedious and repetitive tasks, then to enable the user to participate in the design and construction process. But recently with the popularization of digital fabrication technologies a pleura of design proposals based on digital design interfaces for architectural production emerged that enable a different and more open approach to design and fabrication. Woka is an experiment that associates a doctoral research and a broader investigation of digital fabrication both working towards this goal.

This paper presents an ongoing research about Woka and is organized in the following manner: first we will present the motivations that triggered our investigations and experiments; second we will argue about the research methodology and some similar cases that laid the base for the design process; third we will present the initial prototype and its evaluation; finally we will discuss about the findings and make our conclusion.

1.1 Motivation

For long architects have made claims that the general public should give more value to their work and recognize their importance. That is not different in Brazil, where architectural organizations have been battling to get people to hire architects to design their buildings. This is a strange fact if confronted with the numbers of the federal government that estimates that the housing shortage is of about 7 to 10 millions of
homes. If there is a lot of work why are the architects not involved? So the question is not only how to instruct the users about the importance of the architect, but more important, how do involve architects in the actual construction of the built environment. The Brazilian government is filling this gap left by architects by building thousands of mass production houses creating entire new neighborhoods of standard houses through the federal housing plan *Minha Casa Minha Vida*. To solve the huge housing shortage by building standard cities is highly questionable and to hinder this architects need to think about different ways they can participate in the process. To have architects to design each house in dialogue with the future inhabitant could be an answer, but design is an expensive commodity that only a few can afford. Other strategies are needed to confront this problem.

Alejandro Aravena Elemental houses in Iquique shows a different approach to this problem by enabling some level participation of the user in the design process. Elemental is a profit company with social interest focused on developing social projects. The houses in Iquique are the first experiments on a house typology that involve the user in the construction process. The design of the building leaves a structured open space where people can later continue to build their homes and adapt it to their needs. It is an interesting approach since it enables to optimize the use of public or private investments by building a basic unit that can later be expanded by the user. The money can be directed to buy the land that is normally expensive nearby urban infrastructure, leaving the expansion of the house to the user. The problem with such approach is that people may need to hire another architect to finish the building, or build it without any support. It is true that people have been building without technical support for centuries without much problem, but other strategies may be of interest.
John Habraken proposes one interesting approach to this problem. Habraken [1] developed the potential of customization of open structures and created the concept of support (drager) and infill, in a process called *Open Building*. The support is socially created as a tri-dimensional urban planning and the infill can be individually developed. An important aspect of Habrakens work is the shift from object to process, as for him the most important was how people would participate in the design process. The *Open Building* concept reveals that parametric design and digital fabrication still has a vast field to be explored. *Open Building* was not conceived as a digital tool, on the contrary, it is a series of principles and approaches to architecture regarding different issues and discuss a pleura of questions that the research in digital fabrication processes are trying to cope with.

The key point in the *Open Building* approach lies precisely on assigning responsibility to the user, who participates in the architecture design process according to some principles that insert him into the specific context in which inhabits. The digitization of architectural design processes ensures greater accessibility to those all involved in the process, from the designer to the user. Thus, a more concerned approach to user relationships with the architectural design process, as in the *Open Building*, can be even richer in the context of digital fabrication, which facilitates the distance of a more formalistic approach that reduces the number of specific issues currently dwell in cities. Woka was proposed as a design alternative to explore this potential of involving the user in the design and building process.

### 1.2 Methodology and similar cases

The methodology proposed for this research is based on the association of theory and practice in a heuristical process of investigation. Studies that deal with the use of new
digital tools and technological devices in architecture represent a challenge, because they generally deal with wicked problems. Wicked problems is a concept generalized in design by Buchanan [2] that designates problems that are hard to formulate, where information is confused, the agents involved have conflicting values and the ramifications of the system are dubious. Architecture deals with wicked problems because it is contingent, it is constituted by complex and contradictory relationships continually open to uncertainty. As augmented by Till [3] architecture can't be resumed to one idea or concept that can be research and dissected through traditional scientific methods based on causality. Therefore what is presented in this paper is not a finished product, but an open and continuous investigation that is informed by cycles of design, prototyping and evaluation. The initial prototypes and its evaluation will be presented in the next section, but first we will present and discuss some similar cases that laid the base of the design process.

It can be noticed that a pleura of design proposals based on the popularization of digital interfaces for architectural production recently emerged. Generally they intend to present a digital interface associated with a relatively friendly design that tries to give people access to different digital fabrication processes. Most operate using CNC milling or laser cutter machines to fabricate joints and sections that can be easily assembled. One of the most widespread interfaces is Wikihouse[4].This process, proposed by the English architects Al Alastair Parvin and Nick Ierodiaconou, has as main characteristics the use of the SketchUP[5] software, the definition of design principles and the creation of a shared database. The first design principles define which type of wood is to be used, how to think about the fitting of different elements and its resistance. These principles also cover how one should draw the elements in SketchUp, which is relevant for the Wikihouse, because it uses a plugin designed for this software. This plugin is presented as one of the great advances of the system, as well as one of its advantages. In this manner, Wikihouse is not specifically a house, but an integrated set of processes that enables people to produce an architectural artifact.
The plug-in developed for Wikihouse generates the cutting diagrams, that is, it transforms the 3D model into a file with bidimensional drawings of the pieces that can be read by a CNC cutting machine. This is the automation of a relatively complex task that is executed with one command in the program. As this is an application designed under the Creative Commons license, the Wikihouse encourages sharing of the designs produced with the same logic with other users through the online database. The database is constantly updated and enables an exchange of experiences between different users in several parts of the world such as New Zealand, Brazil and Holland, among other countries. Each of these centers have developed an autonomous and different approach to Wikihouse in their specific contexts, which has resulted in very different experiences.

Besides Wikihouse, we can identify other proposals that have similar principles and approaches, with some differences of nuance. Click Raft[6], Hermit Houses[7] are some examples that have a similar description with Wikihouse and have very similar results. The American architect Greg Lynn, famous for his experimental approach to digital representation technologies and digital fabrication in architecture, also proposes a parametric process for developing a housing system using similar strategies. The project for the Embryologic Houses was an attempt to explore the process of parametric design and digital fabrication to generate a series of customizable houses in different shapes departing from the same design logic. The design enables some level of openness as the geometry can be modified within the predefined parameters of the components maintaining the same structural logic. This process facilitates the customization of different units as all the parameters can be easily manipulated by the architect, but it doesn't involve the user in the design process. On the other hand, one example of interface that enables a higher level of user participation in the design process is Sketchchair[8].
Sketchchair is an open source software developed to facilitate the design of chairs intended for digital fabrication. The system enables the user to control in a simple manner the whole process of design of a chair, including initial drawings, detailing, testing and manufacturing. The interface consists basically in a 2D work plan with drawing and editing tools. The whole process is based on the manufacturing method with ribs, generally called waffle, where the object is sectioned in the longitudinal and transversal directions forming interlocking planes. The user can easily draw the profile of the chair and latter adjust the layers and sections to determine the final shape. The software also includes a system that enables to test the ergonomy and to simulate gravitational forces. The ergonomy test is done with a figure that represents the human body and can adopt different measures. To test the proportions of the object the software dispose of several reference images like tables, other chairs etc. The product is a vector file with all the pieces of the chair that can be sent to a CNC cutting machine or even printed as a mold and cut by hand.
In terms of the discussion on the possible relationship between the principles of digital fabrication and architecture we can say that such systems represent significant progress. However they still have several limitations that represent a few challenges. Although we do not see a system that has reached a full and mature result, that is, which has succeeded in producing large-scale architectures and with the level of diversity initially proposed. Most systems generate products with the same aspect and are generally unfinished. We believe that one of the reasons that gave prominence to Wikihouse is the fact that it is an open system for collaboration, leveraging different dialogues and experiences. Also, because of its choice of software that gave support to the system as SketchUp has a simple and friendly interface design and has become one of the most popular 3D modeling software in the world. The Wikihouse app aims to facilitate a relatively complex task in a very simple software. However, this task is not yet fully developed because it still has many limitations. In addition, to the application to be efficient in practice, it demands a very complex modeling to generate all the necessary parts, which makes the process slower and subject to numerous imperfections. The houses developed with Wikihouse look very similar to each other, which leaves some doubts about the degree of openness of the design process. Perhaps even unconsciously, the architect Greg Lynn used this deficiency as a positive fact, because the houses he proposed were different to each other, but all had the appearance of a design produced by him, which for many represents a brand value in the product.

Fig. 6: Embryologic Houses by Greg Lynn

Besides the used marketing strategy, the fact is that for open systems and supposedly, largely parameterized, the similar results show a low diversity, which it could mean a low degree of openness to one who uses it. This means that these systems could be promoting a poor dialogue or no dialogue between those involved.
The design principles end up becoming more a formal rule than a coherent set of parameters that facilitates the architectural design.

Another aspect that should be highlighted is that most systems only include the use of new materials such as plywood, failing to consider the use of existing materials available on the context of use. Of course this is a task that would make this systems even more complex, however it enables a more sophisticated approach to the existing contexts, generating more specific and less generic solutions for each design problem. These systems still don’t explore the potential of the use of modular coordination principles. The fact that they are parametric, or present ability to be, facilitates the task of carrying out this type of coordination. The more this coordination relating to the use of existing materials, the more such systems opens to diversity, abandoning the emphasis on aspects often purely formal. This is not a simple task, but the rise of digital fabrication tools and the share of information through open source communities permits us to operate this complexity, empowering more individuals to deal with it. In this way such interfaces open to different possibilities for dialogue, which extends the range of solutions.

If we compare the Wikihouse to other systems such as Click Raft and Hermitt House we see that another subtle difference expands its potential use. The Wikihouse defines some principles of design while the others already define a shape. Although most of the principles of Wikihouse are essentially formal, there is a minimal concern in the user input in the design process, which opens a possibility for dialogue. At the same time it reveals how parametric systems have enormous potential to trigger dialogues, especially if their basic assumptions include the user's as co-responsible for the production of architecture. In this sense, digital interfaces for architecture show greater potential for dialogue and, consequently, increase the variety of solutions, if they are more based on principles that enable the individual intervention of those who inhabit those spaces, giving them the tools to act.

In this sense, Woka avoids the use of the Wikihouse plug-in because of its problematic aspects and seeks to develop some procedures to optimize the 3D modeling tools. The interface in Sketchup was built on dynamic components with simple commands, like stretching, clicking and scaling. The most important feature is to leave a level of openness to the user to choose different materials and configurations. This openness allows the creation of a variety of different outcomes. The next section will explain in more detail how this process works by discussing the first prototypes.

1.3 Woka 0.1 – First prototype

Woka is not a finished house, but an open construction system based on parametric design and digital fabrication intended to trigger the design and building process. The idea is to generate a inner shell that is immediately deployable combined with a more durable outer layer that can be added later with conventional building systems available at the site. In that way people can create an initial proposal to respond to their immediate needs, change and adapt their design on site by reconfigure the parts and use their own building culture and collective knowledge to finish the
construction. In that way the systems enables the dweller to add his experience to the design based on his own culture and different ways of inhabiting. The Wikihouse concept was used to create a module that can be dynamically changed in Sketchup. A dynamic component was created that can be stretched in two directions and be combined to other different components. A plug-in called Bimbon[9] (www.bimbon.com.br) was used to automatically generate the building cost and material specification, so that with each modification of the original design the estimate cost is recalculated.

An important change proposed to the Wikihouse system was to create a dynamic component drawn in Sketchup that consisted of the detailed drawing of the whole rib structure. We chose to use the detailed version to create a direct correspondence of the representation of the module with the elements that were going to be fabricated. Because the Wikihouse plug-in failed to create the right joints we abandoned it and used the design proposed by the New Zealand group Space Craft[10]. Since the structure proposed by Space Craft was already designed and calculated to resist earthquakes it was a reliable set to work with. The use of this dynamic component was of great importance to enable unskilled users to manipulate the drawings, since simple commands can alter the form and configuration of the house.

The fabrication process is based on a 3 axis CNC cutter (laser or router) and consists of a rib structure built from plywood sheathed with OSB panels. The product is immediately deployable, can be easily mounted, dismounted and transported. The possibility to customize the sections and joints and to fabricate it fast with high quality enables the inhabitant a different living experience as the modules can be used in diverse situations and possible scenarios. It can be used to build a house, an annex of an existing house or even a office or garden house. The polyvalent nature of the system and its low cost enables many solutions to take place and fits to reality of each one.
The first design consisted in a house with one sleeping room with balcony, one bathroom, one living room and a kitchen using in total five modules. It was chosen to keep the design as simple as possible to enable its construction and evaluation with a low budget. The roof joints were designed to facilitate the use of insulated metal roof tiles that also covered the facades, and also enabled the use of other materials. Part of the house was covered in glass to expose the rib structure because of the experimental nature of the first prototype. All the interior was coated with OSB panels, including the floor and ceilings. The final cost of the construction calculated with Bimbon was of $6000,00 dollars, which is still expensive for low cost housing in Brazil. What elevated the cost was the price of the CNC cutting of the plywood plates which is still very elevated. Because most of the machines available are used in an industrial context there are few that are willing to stop their production to enable this kind of project.
One section of the house was fabricated in a 1 to 25 scale to test how the joints worked in the actual material. The premise was that if the structure would work in a small scale it could have a similar effect in a 1 to 1 scale. The prototype proved easy to fabricate and assemble. Although this can't be said to be true in a 1 to 1 scale it seems that it will work likewise.
1.4 Discussion

Traditionally, most architects use processes based on prescriptive digital representation that allows little or no openness for user participation in the design and creation of the architectural space. When trying to control all design parameters in an attempt to predict possible errors, define situations and configure form, the architect may end up restricting the potential for a more creative architectural appropriation. In extremely complex systems such as architecture the number of states of the system is exponentially greater number of states that the architect is able to anticipate. Thus the only way for the architect to exercise control over the project is by restriction, since according to the Law of Requisite Variety [11], for a given system to control the other is necessary for the controlling system to have at least the same amount of states as the controlled system. Glanville [12] compares this type of control by restriction with dictatorial systems that work based on power relationship. In this context the architect operates by defining the form and by restricting the possibilities for more open appropriation and use. In contrast, Glanville [12] argues that to lose control can be a strategy to expand the number of options available allowing us to be more creative. To Baltazar [13] an alternative to break with control, restriction and limitation of the design is to think architecture as open process, establishing continuity between design and use. This openness can be reached by opening the design parameters to be manipulated by the user.

The opening of design parameters to interaction with the user can significantly increase the number of states of the system, expanding the number of options available. The method of producing architecture as well as the work of the architect is substantially modified. But unfortunately it does not happen in practice and architects, in contrast, face an ethical problem by restricting the increase of the number of possibilities to their practice in the office, not extending them to the end user [14]. In most cases the parameters are crystallized in final form, that remains closed and unchanging. This is aggravated by the transduction of the coordinates and vectors in physical matter on the basis of digital manufacturing processes. Shell [15] warns that this physical rendering of codes in finished products can skip an important step of the possible transformations of initial design during execution. In this sense Woka was designed to trigger a building process, and not as a finished product. The idea is to establish a continuous process of design, fabrication and use of the architectural space. This is possible because the system enables a fast assembly and disassembly of the constructive elements. People can easily rearrange the spatial configuration by changing some elements and by fabricating new elements and joints. This joints can be designed by the user or downloaded from an online database. In this way the parameters are open in the design and fabrication process. A limit in the opening of parameters was established so that the basic module can be immediately deployed, even if the outer shell is not rapidly finished. In this way the user will not essentially need another architect to finish the building.

Woka can be associated to the concept of open design that is defined by Paul Atkinson [16] as "the collaborative creation of artifacts by a dispersed group of otherwise unrelated individuals and of individualized production". This concept is
related to a movement where individuals collaborate to the creation of knowledge, objects, cultural production, services, etc, that has been given a great impulse since the popularization of the internet. Atkinson [16] notes two aspects that should be considered to make the open design technologies more acceptable to a wider public: the development of more user-friendly interfaces with a more intuitive system for the creation of tridimensional models; the distribution of more appropriated materials for the use in digital fabrication machines. The role of the designer goes from the design of closed objects into the design of interfaces, or processes, to provide user with support to create their own design. Jos de Mul [17] calls this new process database design, where the designer doesn't design objects, but creates a drawing space where inexperienced users can access user-friendly interfaces within which they can draw their own objects. In this sense the designer creates a metadesign that only materializes as product through the interaction with the user. The creation of these metadesigns may represent a possible alternative to the increasing control exercised by architects in the design and construction process, made possible by the association between parametric modeling and digital fabrication.

The idea to create interfaces to enable unskilled users to access complex data is not new. In the early days of the computer it would be difficult to imagine that a computer would fit in a pocket and be used by almost everyone, regardless of education or age. What made this possible is a combination of factors where the interface plays a big role. A evidence is that computers are today several times more complex and faster than in the early days, but are much easier to use. In that sense, the creation of the dynamic component in Sketchup that allows the user to easily manipulate the design is of paramount importance. Although it may appear that parametric systems can be difficult to be manipulated by unskilled users, the questions lies not in the level of complexity of the system, but in the design of the interface.

*Woka* reinforces that the digital fabrication technologies, when approximated to architecture, open the possibility for the participation of the user in the conception of space, making him co-responsible for the design. Jones [18] also advocates the shift of the focus from product to process, since the goal of the design should not be the finished product with a particular function, but the very continuity of the design process. For Jones [18], in the process everyone is a designer. In this sense the focus on the process allows the user to transform into coauthor of the design of the architectural space, increasing its active role. In one level *Woka* inserts, even in a preliminary way, the user in the process, allowing him to take some key decisions for the realization of each project. But in a second level, the user may share his design experience in the database to participate in the cycles of iterations, blurring the distinctions between user and designer.

### 1.5 Findings

*Woka* was developed as a dialogical design process that empowers self-builders to act in a more autonomous way, expanding the traditional role of design practice and the way buildings are created. The way to produce architecture, as well as the work of the architect, are sensibly modified. The role of the designers shifts from the creation of
designs to metadesigns that only materialize through dialogue with the user. Our initial experience with Woka revealed that the creation of metadesigns is a complex task because of a list of reasons. First because of the need to create interfaces to enable people to access the design parameters. This interface have to be simple enough to be easily accessed by a non proficient user and as complete as possible to enable the manipulation of parameters. Second, by reason of the importance of the design principles over geometry and building form. It is important to enable a real participation of the user in the design process without constraining possible outcomes and use of different materials. Third, by virtue of the necessity to choose which parameters are left open to be manipulated by the user and which are not. Finally, as a result of the need to create or use an existing database to feed the different cycles of iterations and dialogues between different users and designers. Woka is a work in progress and by cause of its nature may never become a finished product. But the work already developed raised a series of important questions that advance the discussion about the use of parametric design and digital fabrication in architecture. In this way Woka challenges this traditional process by using dialogue as a design approach, shifting the focus from the object to intersubjectivity, amplifying the potential for novelty to arise.

Although some advances were made, there is a long road to reach a more sophisticate and complex metadesign that will empower people to create their environment. The next challenge in the process of development of the Woka system is to further investigate the possibility to associate the digital fabrication system with more common building materials, and to explore more intuitive interfaces for design.

Aknowledgements

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Urban prototyping

Socializing the design to fabrication process

Dermott McMeel¹ and Charles Walker²

¹ University of Auckland
² Auckland University of Technology
d.mcmeel@auckland.ac.nz, charles.walker@aut.ac.nz

Abstract. Within the context of burgeoning urban populations and the rolling back of state resources, there is growing interest in ways in which citizens may participate in the creation of resilient and livable cities. This paper proposes the concept of ‘urban prototyping,’ and employs a design research methodology to develop and document the socially-sponsored design and digital fabrication of an urban shelter. We explore how we might use networked design and fabrication technologies to leverage the social capital locked within non-professional communities so that our current cities might evolve into whatever our next cities need to be.

Keywords: participatory design, urban, prototyping, eco-digital fabrication, expertise, design futures, value frameworks.

1 Introduction

Both the urban environment and the design professions are experiencing change. Seventy-five percent of the global population is predicted to be urbanized by 2030 [1], yet most designers serve only a tiny percentage of that population. While design and construction are necessarily highly regulated, there is some urgency to make them more consumer-friendly and democratic[2]. The increasing accessibility of digital fabrication, desktop manufacturing tools and makerspaces offering open source and DIY tools and software, also causes us to question the protected position of the design and construction professions. How might the architect or designer operate in communities with increased access to networks of information, diverse expertise and new technologies?

In this paper we present a research project that investigates how, and to what extent, design and construction might be democratized[3]. We document the design of a prototype 10m² shelter within a ‘software ecology’. We aim to enable the encoding of key aspects of a design as well as the capability to pass other design and creative freedoms (that are traditionally the preserve of the design and construction professions) onto the citizen. We employ the notion of ‘urban prototyping’ to unpack the discourse around how we might cede certain responsibilities to communities.

without abandoning the professional obligations to quality, health and safely. Finally we discuss how the unit was appropriated when complete and note some of the unexpected consequences of devolving aspects of the design and construction to a community.

2 An Urban Prototype

In this section we document an urban intervention aimed at exploring potential design futures. EDFAB (eco-digital fabrication) is a research project funded by the University of Auckland and its Thematic Research Initiative ‘Transforming Cities’. Its aim is primarily to deepen our understanding of how changing technology alters skills, knowledge, practices and processes within the building sector as well as explore how social capital can be utilized within a modern urban context.

Previous work has explored how emerging digital technology has changed supply driven markets into more democratic demand driven ones [4], here we extend this discourse to investigate how design and construction can be more consumer-friendly.

Flat pack furniture already offers a potential methodology, where the design has been carefully considered for ease of assembly. Another is makerspaces or hackerspaces, the phenomenon of multi-use spaces that bring together a variety of design and manufacturing technologies and encourage the formation of public and/or non-professional communities of practice. Tools such as computer numerical controlled (CNC) routers and laser-cutters, which were until recently rare and expensive, are now relatively easy to access in many cities. This dramatic increase in digital technologies and services also creates new possibilities for developing alternative pathways from design to production. Typically, these rely more on the modeling and transfer of digitized 3D information models and less on abstracted 2D drawings. In the following section we prototype a possible ‘design to production’ future through the design and construction of a small 10m² unit. We develop a construction methodology, design and prototype the software infrastructure around it as well as use existing manufacturing tools in its fabrication and construction.

2.1 Context

If some of the key anthologies on digital fabrication[5], [6] and its stakeholders are examined[7], [8] a preoccupation with form becomes apparent. This is perhaps because digital fabrication most obviously lends itself to the efficient production of otherwise prohibitively complex forms. However, as both professionals and students become more familiar with, and desensitized to, the novelty of digital fabrication, a new criticality is emerging, questioning the values and benefits of emerging tools and techniques, such as linear kinematic robotics, nanotechnology and 3D printing.

Karl Marx[10] exhortation that the potential of automation is not about prosperity, but about the dangers of dehumanization. Although Marx was referring specifically to the workers who are replaced by technology, we might also apply this critique to the
possible consequences of digital fabrication. Our recent history of prefabrication, when in its adolescence, created dehumanizing mass-produced housing. As a new wave of technology emerges, we have a responsibility to explore the potential not just for seductive form or efficient construction, but also to consider the lived experience of individuals and communities in their engagement with new technology. We seek to explore the deeper societal potential of technological changes, as well as the more immediate design and construction innovations.

The EDFAB project (Fig. 1) began by proposing to build and test a small timber based unit using some digital fabrication techniques that we had seen emerging in Europe and North America. The aim was initially to test the potential benefits of a ‘do-it-yourself’ (DIY) approach, and whether such a system could conform to New Zealand standards.

A ‘sleep-out,’ a freestanding additional room, is a traditional addition to the New Zealand suburban home. It is typical constructed in a ‘do-it-yourself’ fashion and although it benefits greatly the owners or occupiers, its ad-hoc construction causes problems. It can be damp, draughty, cold in winter and overheat in summer. The research takes its inspiration from other businesses such as furniture able to use digital fabrication to prepare some aspects of an object prior to shipping so that DIY assembly does not compromise the quality of the built object.

The project is located in Avondale, a neighborhood of the city of Auckland, New Zealand. Although Auckland is a relatively low-density city, recent population growth has exacerbated high land prices and a very aggressive housing market. Arguably, the city is becoming unaffordable for the average citizen. In Auckland it is possible to see how the existing neo-liberal design and construction procurement model could potentially fail to fulfill demand and the provision of healthy affordable homes.

Fig. 1. The EDFAB construction system to build a ‘sleep-out,’ a common addition to NZ domestic space
Using Rhinoceros and Grasshopper 3D modeling software it was possible to create a parametric description of the ‘sleep-out.’ This software could automatically subdivide the unit into a number of rectangular box-like parts, then automatically compute the cutting templates that could be fed directly into a CNC router for fabrication (Fig. 2).

![Fig. 2. Cutting templates, assembled into boxes, and boxes constructing a building](image)

Through this process, constraints became opportunities. The depth of the unit was limited by the length of available plywood boards (2400mm) and the length was limited by the span possible using our chosen size of timber beam. By encoding constraints into the software, it was possible to avoid a user specifying dimensions that would result in parts that could not be fabricated out of standard plywood panels, or if fabricated, would potentially be structurally unsound. With these constraints encoded in expert software, it became obvious that we could create a very easy-to-use computationally light desktop application that would enable a user to manipulate and tailor a unit’s size to their specifications (but within the encode constraints). When a particular size was agreed upon, the information could then be communicated to the expert software that would then undertake the computationally heavy generation of all the cutting component templates necessary. Making available a variety of customized solutions matching the pre-set constraints affords certain freedoms to the end user (a client or prospective owner); freedoms that typically have to be carefully managed as they can easily delay or complicate a careful programme of design and construction. Traditional skills such as structural and environmental design expertise remained critical, but they could be shifted from the late design phase to the initial one, i.e. during the development of our software and data interchange protocols. New skills were also required in the form of software developers, in particular ones that were attuned to design and construction. For this stage of the project, we were able to find them within the Department of Architecture, confirming what McMeel and Amor [4], [10] have discussed elsewhere, i.e. that the skillsets of emerging architects increasingly involves sophisticated computational abilities.

Communication is critical during design and construction. Paper drawings are a long established means of transferring information between the multitude of professions and trades necessary to deliver a finished building. Drawings have evolved into a very effective tool to communicate, coordinate and help disparate stakeholders converge on a common understanding. DWG (the proprietary file format of AutoCAD) and DXF (Drawing eXchange Format) are the digital equivalent and have been used successfully since the 1980s for exchanging geometry in the form of drawings and models. We are, however, in the Information Age where CAD
(computer aided design) has given way to BIM (building information modeling). Geometric models have given way to information models and exchange formats such as DXF and DWG have given way to IFC (Industry Foundation Classes) and CoBIE (Construction Operations Building Information Exchange). These digital standards and conventions seem in keeping with their paper predecessor, but there is a stark difference. Whereas drawings are a means to mediate the different languages, grammars and ontologies that make up the building process, these emerging standards are languages of themselves and, although they are descriptively adequate to communicate between virtual stakeholders, they are neither particularly efficient nor particularly optimal for communication between any roles or disciplines.

McMeel and Lee [11] have scrutinized construction ontologically and theorized an emerging pre-ontology, which provides a framework to conceptualize these communication conventions. However, they remain highly problematic in so far as the notion of a pre-ontology, be it in the form of IFC or CoBIE, does not seem to have a natural resonance with industry stakeholders. The industry’s resistance to the uptake of these communication conventions is well documented. Design and construction is—like nature—a competitive ecosystem where the fittest and leanest survive. There is no room for inefficient communication, no matter how comprehensive it is.

Let us turn for a moment to the natural world’s complex ecologies and communication systems. Where one insect uses color to fend off a predator, another uses scent to attract a mate; each affords specific and clear channels of communication. In *Life Itself*, theoretical biologist Robert Rosen[12] has conceptualized this in terms of ‘dictionaries.’ Each channel of communication has two dictionaries associated with it, one at each side of the communication channel, for encoding and interpreting the signal. Rosen makes it clear these dictionaries are not necessarily the same, but they are highly efficient. As an ecology grows, so do the number of dictionaries, but importantly they are quite simple. It is the aggregation of these channels that makes for a complex ecology. This is in stark contrast to communication within the AEC (Architecture, Engineering and Construction) industries, where best practice is often to implement a complex interoperability protocol, which is highly technical and somewhat overwhelming. It is perhaps then natural that they are resisted.

In EDFAB we took a fresh look at communication and used Rosen’s concepts of natural communication to inform our strategy. In the following sections, we detail the three parts of the project, the construction method, expert user interface (xUI) and the end user interface (eUI). We will discuss the parts of the EDFAB ecology and how the efficiency of the communication protocol was addressed.

2.2 Construction

Exhaustive surveys of the impact of technology on human interactions in office environments have been carried out by Robert Kling[14, 15, 16], an expert on the study of social informatics. One of Kling’s key findings, which we might take for granted today, is that where technology is introduced unexpected things happen.
Often this is as a consequence of technologies' effect on human interaction. Technology alters the ease or difficulty with which we communicate, skill sets need to change and roles become redefined. He also recognized that technology is sometimes implemented for political reasons. In such cases, Kling found there is often little evidence that politically-motivated change actually delivers overall improvements. Turning to construction, we have lessons that can be learned; firstly to exploit digital fabrication technology change is necessary and secondly these changes will likely have consequences well beyond the places they are implemented.

In the last ten years a method of construction has been emerging and documented[3] that capitalizes on digital fabrication. This method has been used successfully by Facit Homes, a bespoke house design and manufacturing company in the UK. The system breaks a design down into building blocks; one might draw the analogy of a LEGO system for grownups. Each block is then broken down further into flat pieces that can all be cut out of standard sheets of plywood by a CNC router and easily assembled. The blocks are easily carried by two people and built up on site.

This system was modified to accommodate the plywood availability and building standards in New Zealand. A 1:1 scale prototype of one section of the sleep-out was built (Fig. 3) to test the system, detailing and tolerances. This information will be built into the digital models and software interfaces to ensure some similitude between the digital model and the final real building. The system uses a ‘butterfly’ plug that is hammered into place between each block; this interlocks the blocks and creates a robust structure. In Europe the current best practice is to tape the joints in lieu of wrapping the structure in a vapor barrier membrane.

![Fig. 3. 1:1 prototype, digital model and 1:6 scaled model of the sleep-out](image)

During this process a number of factors emerged. Locally-available New Zealand plywood for general building construction is not as dimensionally stable as its European counterpart. Latvian Birch appears to be the plywood of choice for this method of fabrication and construction. Imported Chilean plywood was also used and also found to have deviations that cause problems for digital fabrication. Even with these stability issues it was possible to construct the 1:1 section. Having completed the section of the 1:1 model and modified some details, a 1:6 scaled model (Fig. 3)
was construed to assess the new details, the overall construction concept and also to check for ‘creep’, i.e. the phenomenon where small deviations in the physical construction are aggregated over the length of the building causing the combined components to be of a different length than intended.

2.3 Software

The expert user interface software is closely linked to the construction technique, as much of what was learned through the building the prototype and model was necessary, as aspects of it would be encoded into the software interface. The interface is built using Rhinoceros (http://www.rhino3d.com/), a popular 3D modelling software, in combination with Grasshopper (http://www.grasshopper3d.com/), a parametric plugin that provides a ‘procedural’ interface for Rhino.

A sense of the complexity of this process can be gleaned from Fig. 4. At the extreme left we have an illustration of the software, the center diagram is a detail of its complexity - each box represents a calculation or decision. For example, one of these boxes contains a detail drawing of our butterfly joint. If we decided to change the joint we could change the detail once and have it changed throughout the project automatically. The illustration on the left of Figure 4 represents only fifty percent of the software, which executed choices and decision based on what we have learned from building the prototype section and the 1:6 model. It is interesting to look at an image of what is essentially a digital encoding of the design decisions necessary to create the construction components from a 3D model. It gives us pause for thought about the complexity of a typical design and construction process, where here there are literally hundreds of interconnected decision and choices necessary to deliver a relatively small and regular shaped building.

The only input the expert system needs is three Cartesian coordinates that represent the length, width and height of the sleep out. With the deepened understanding of the system we could impose limits on these dimension to ensure constructability and structural stability. With this in mind we commissioned a standalone easy to use application that could be downloaded by an end user to tailor their design
requirements. Concurrently we were devising a communication protocol to exchange information between the end user interface (eUI) and the expert user interface (xUI).

The eUI: end user interface (Fig. 5) was written in C++, which was chosen because it can be compiled to run on almost any computing device, such as Windows PC, Mac OSX or handheld devices running the iOS operating system from Apple. None of the sophisticated construction information is replicated here. This is a simple application that gives the end user the visual appearance of the sleep out construction, and offers the ability to easily change some of the dimensions within the limits we have specified. A silhouette gives a sense of scale and there is an approximate floor area provided – a value that is useful to a potential end user. In essence, having worked through a processes to capitalize on digital fabrication and build software that enable us to leverage the benefits, we have been able to pass certain freedom, in this case design freedoms, onto the end user. These design freedoms are not afforded under traditional design and build processes as they have the potential to compromise the construction programme.

When the need for information exchange arises within a traditional design and build programme, a geometric model interchange standard is used. Most of the standards for digital information exchange in the AEC industries are for communicating geometry (OBJ, DXF, DWG, 3DS). Within our ecosystem we have no need for communicating geometry. Instead, we need to send some coordinate information and the xUI will build the geometric model according to its needs, initially we explored IFC and CoBIE, which have been mentioned earlier in this paper. Both are very comprehensive but IFCs have a very complex syntax associated with them and CoBIE seems to privilege a spreadsheet layout, which is not optimal for application data interchange. We instead adopted a CSV (comma separated variable) file syntax, which has a very simple structure (Fig. 6). This file type is
quite common for transferring information to and from databases and subsequently is suited to both data exchange and to efficient digital communication.

This was the simple ecosystem we developed to leverage the possibilities of digital fabrication. It is still a work-in-progress and at the time of writing we are exploring the possibilities of further structural encoding as well as utilizing JSON (JavaScript Object Notation), a file type that is very popular for data exchange, particular in the burgeoning area of GIS (geographical information systems) and geospatial data, when vast quantities of data need to be transferred quickly and reliably.

3 Analysis

The implications of this research for design and construction will be discussed through three themes, they are: expertise, design futures and value frameworks. While this work in progress was not without challenges that prohibit a prescription for success, we can draw from it a number of lessons.

3.1 Expertise

What is perhaps most apparent from the design and building process outlined in section 2 is the extensive, specialist and cross-disciplinary knowledge required in its realization. The unit is in no way exempt from building regulation and still has to comply with the plethora of codes and guidelines. Rather than becoming redundant this knowledge continues to be important. So although we were able to encode aspects of the building code, it was still necessary, in the first instance, to draw on experts with this knowledge. In fact, if we look at design and construction in general there are
an increasing number of specializations, in resilience and environmental efficiency, for example, which continues to support the argument that knowledge and expertise is key in the design process. Although this is not without economic impact; increasing specializations increases the size of the design team and ultimately the budget. In light of WikiHouse founder Alistair Parvin’s claim that the architecture profession only reaches one percent of the global population [2] there would seem to be an urgent need to make good design more, not less, accessible and economically viable.

Although the research project documented here was modest in scale it offers a more consumer-friendly design and construction methodology, which is both more accessible and economically viable. It is similar to many popular consumer-friendly furniture concepts where the complexity is engineered into the parts, leaving assembly much simpler.

### 3.2 Design futures

The research raises the two-part question ‘to what extent can a design to fabrication process be encoded, and made easier to use by non-experts?’ Although our encoding was limited to structural guidelines, it may be possible to encode important design principles. Using geo-location to encode wall construction for thermal performance or encoding window and door size and orientation to capitalize on natural heating and cooling principles seems a logical step.

The development of the software ecosystem created the possibility of more personalization by an end user. Initial experiments with prefabrication in the 1950’s resulted in a high degree of standardization in housing, which because synonymous with social deprivation. While recent off-site manufacturing trends have brought some choice back into the prefab market, Toyota homes are perhaps the most extreme example [17]. While prefabrication continues to improve the provision of choice, the utilization of the parametric architecture in our system offers the possibility of extreme personalization within a fixed prefabricated system.

### 3.3 New value frameworks

The construction system was intended to be accessible and during the building process we had participation by members of the public, including children (Fig. 7). An unexpected side effect of the construction system was the extent to which the process was highly social. We attribute this to the considerably reduced risk that the digital fabrication process afforded construction. Also the highly technical aspects, such as structural engineering had already been designed into the system, leaving the construction process more akin to building ‘Lego.’ It was relatively safe and a very tidy construction process. Upon completion, while the rest of the site was slowly reclaimed with graffiti and vandalism, our prototype unit was not (Fig. 8). A local gang initially claimed it as a base by hanging their ‘official’ colors on it and moved furniture in, before eventually a local homeless person appropriated it for sleeping.
Fig. 7. Children joining in the construction process
4 Summary

This prototype was constructed in the suburb of Avondale in the city of Auckland, a community that has recently been made responsible for a number of initiatives by the local council. Including a survey to gather data on where residents would like change, festival organization and art brokerage. As this trend is set to continue the research has investigated a possible future where some of the aspects of architecture have been ceded by the design and construction professions. Perhaps most interesting however, was the sense of community-ownership that developed around the build and persisted as resisted vandalism and was appropriated by a gang and the homeless.

The design methodology, construction system and software ecology that grew around it point to alternative models of design, procurement and building. The intention was to investigate how, to what extent, control of design and construction can be ceded to citizens. As individuals and groups often have valuable knowledge about the community and what is and is not required.

This research extends the discourse beyond the provision of installations for temporary activation and explores the concept of ‘urban prototyping’ as a means of advancing the discourse on how future cities will be designed, procured, constructed and regulated, and presents a possible design future that is more economic, egalitarian and sustainable.
Further research will examine potential changes to public infrastructures, investment and organizational systems that will be required in order to demonstrate scalability of the participatory pilot project explored here.

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Abstract. This work aims to investigate the concept of smart city within the Internet of Things (IoT), and analyses possible transformations of urban space in areas of surveillance and control. As already seen regularly in the media, surveillance and control of data on the internet is a problem that affects personal freedom. If similar surveillance system is applied in the Internet of Things, where people, objects and environments are interconnected, exchanging a huge volume of data, the problem substantially increases due the possibility of more control over various aspects of people's lives. The purpose of this paper is to do a critical reflection about the consequences of the smart city regarding the public space and privacy of the inhabitants.

Keywords: smart city, internet of things, public space, privacy.

Introduction

In the last two decades, the internet promoted several social, technological and economic changes, enabling new ways of communication in time and space. When it was restricted in the digital domain, the internet has caused a revolution in communication. Now that it is coming into the physical things and environments, the changes will be deeper and have even more impact. The new networks that gathers objects, spaces and people all connected are the so called Internet of Things (IoT), and it has just begun.

On the Internet of Things, physical objects and places are endowed with informational capacity and interconnected in digital networks of communication. Subcutaneous sensors, power management, wearable devices, such as clothing, watches and glasses, appliances, home automation, automobiles, bicycles, and streets and public spaces are able to collect and send data on the Internet.

It is a reality that is already visible in the present and it is expected to grow more and more in the next ten years. According to the Pew Research Center (Anderson and Rainie, 2014), in 2025 the Internet of Things should be part of everyday life. The “info-communicative power” of IoT "widens its influence on the world and this on it, from anywhere. This produces a change in their behavior from this relationship. The object gain, so to speak, life“[1].

It is noticeable that one of the concepts underlying the IoT is the ability to use resources and make intelligent decisions in a global field of information. This concept is evidenced in the use of the term “smart” to designate intelligent objects and applications related to the Internet of Things. Usually the smart objects or systems are associated with the incorporation of a processor, a unique identity, ability to connect and be controlled, so they can collect data and communicate in the digital networks. However, the digitization of everything opens up possibilities that deserve to be investigated, says Giselle Beiguelman:

_This will require profound technological changes and imposes a wide range of ethical and political discussions, since the idea that IP address (Internet Protocol) will be related to everything – from places to consumer objects - presupposes a tracking scale, and a degree of creative interconnectivity, unprecedented._ [2]

These issues bring an incisive debate about the definition of the limits between public and private spaces, since the current digital media already caused a blurring of places, when everything is connected to each other will be much more complex to realize the edges and distinguish the private from the public.

The reports of WikiLeaks and the experience with the web have shown that surveillance and collection of personal data by national security agencies and information companies have the capacity to monitor all activity in the digital environment. When this problem is extended to the Internet of Things the control and access to private information can be totalizing and a risk of a serious problem on personal freedom by making public the intimate life.

In this context in which objects, equipment, environments are interconnected through multi-sensory forms, the body's relationship with the networks will be more immersive, and truly the internet will be embedded in a more visceral way in the human life. Therefore it is necessary to rethink the relations that things will perform on other objects, places and people, operating remotely, and what political and ethical problems may surface. The most obvious problem is the production of emotional and personnel input that may be used in targeted advertisements or forms of governmental control and monitoring, as stated:

_There’s simply no way to forecast how these immense powers -- disproportionately accumulating in the hands of corporations seeking financial advantage and governments craving ever more control -- will be used. Chances are Big Data and the Internet of Things will make it harder for us to control our own lives, as we grow increasingly transparent to powerful corporations and government institutions that are becoming more opaque to us._ [3]

In the sense it is opportune to think about the presence of digital networks operating for the sake of the city. Information technology companies aligned with
polity are developing gadgets, instruments and tools of monitoring, surveillance and management of resources to be embedded in the urban structure. These apparatus are the keystones behind the controversial concept of smart city, advertised as a technological hope for a better life of the citizens.

The proposal of the intelligent city

If the technological city of the future is called smart, the normal and traditional cities of nowadays lack for intelligence. So, what relies on the concept of a smart urban environment? There are many definitions of smart city, but the ideas of optimization and efficiency are commonplaces in their descriptions.

The Intel Collaborative Research Institute investigates the “developing and deploying adaptive technologies that can optimize resource efficiency” [4] of the cities. The electronic company Siemens offers solutions to “optimize existing infrastructure, increase efficiency” of the urban space. The information technology company Cisco talks about “mutual and recurring solution improvement to optimize city operations and spending”, and aims to “deliver superior services with far greater efficiency” [5]. The project Microsoft CityNext is “designed to empower governments to create more-efficient city operations” and “to enable government administrators to optimize their citizen-centric services” [6].

It seems that the modernist Charte d’Athènes and its proposal of functional city still echoing in the desire for optimization and efficiency, which could only be achieved by digital technologies devices and services in the domain of smart cities. This ideal project of the city has autonomous decision-making process that knows exactly what to do in the correct time, and it is powered by IoT, where all systems are integrated. Water and energy management, traffic jam, accidents, crimes, riots, air pollution, climate, and all sort of events are intermediated by interconnected digital networks that process the better options to solve problems, regulating and keeping the city under control.

But this attempt of perfection achievement goes against the nature of human behavior that is influenced by all kind of unpredictable circumstances. The urbanist Adam Greenfield highlights that the smart city concept gives no space for spontaneity, the whole city and citizens are subject to the follow strictly a master plan of efficiency:

 [...] everything those residents ever do — whether in public or in spaces and settings formerly thought of as private — can be sensed accurately, raised to the network without loss, and submitted to the consideration of some system capable of interpreting it appropriately. And furthermore, that all of these efforts can somehow, by means unspecified, avoid being skewed by the entropy, error and contingency that mark everything else that transpires inside history. [7]

The fast growth of the urban population is a repeated argument used to justify the implementation of smart city technologies. The crescent rate of the world population
living in an urban space, will impact in more people using natural resources, more consumption of energy, production of waste, increase of transportation, and other basic needs, making more pressure on the city infrastructure and organization. So here comes into play the role of smart city, as stated by Smart City Institute of HEC-Ecole de Gestion de l’Université de Liège: “The concept of smart city emerges more and more as a strategy to limit the problems inferred by the growth of the urban population and to find innovative solutions to meet this challenge” [8]

Find out the innovative solutions can be understood as possibility of entrepreneurship. The smart city becomes a fertile ground for companies and business of information technology to implement their systems. The ambition of IBM does not seek a city market, but globally, as its campaign says: “let’s make a smarter planet, city by city.” It may sound strange that a single company could be a city administration partner everywhere in the world, with access to a large amount of data, including personal information. It is an enormous power concentrated in the hands of a few. Multinational corporations already mentioned before, like Cisco, Siemens, IBM, Microsoft, among others have developed products to transform the normal city into a sophisticated and interconnected city.

**Big brother effect**

In Brazil there are two ongoing projects led by government and big information technology companies that are a clear example of IoT resources applied into the city environment: the Operation Center in Rio de Janeiro was developed by IBM; and Detecta in São Paulo was developed by Microsoft.

The Operation Center in Rio de Janeiro was built to monitor flood and rain problems that seasonably cause landslide and human loss, but has evolved to a more complex center of information to work during the Soccer World Cup in 2014 and the Olympic Games in 2016. There are 30 government agencies, like civil defense, transit department, security forces, police, fireman, urban cleaning, and concessionaires like subway, energy, road company, and others working together and integrated in the same place. These agencies share in real time the images of about one thousand surveillance cameras spread all over the city of Rio de Janeiro. There are sensors in the city to collect climate data. The Operation Center gets satellite information and meteorological data. Google has developed an especial map system that helps to cross the data and visualize geolocated events. Everything is displayed in the huge screen of the control room, round the clock, seven days per week (Fig. 1).
The website interface of Operation Center has indicators of the normality level of the city, bulletin updated regularly for download, traffic jam alerts, weather forecast, security guides, meteorological maps, and the user can view living cameras (Fig. 2). All these data are published in real time. The mobile app *Olhos da cidade* (Eyes of the city) allows the users to share information about incidents and problems on the city.

It looks like an amazing technological control room with integrated services, all connected in digital networks. It is a complex infrastructure. The operators can see the traffic light colors, send text information to the electronic-message sign. When there’s rain with risk of landslide they can play an alarm, send SMS to the residents. The Operation Center has indeed a great capacity of control and surveillance.
Detectaís based in the security program Digital Awareness System (DAS) developed by Microsoft and New York Police Department, and last year was installed in São Paulo. The system can identify thousands of crime patterns and track suspects, read car’s license plate, with a crossed database from the different police forces and from emergency telephone callings (Fig. 3). The DAS has image algorithms to do a filter search of suspects, for instance the color of clothes and personal characteristics. It looks for abandoned packages, suspect behavior, and like in the science fiction movie Minority Report, could avoid a crime to happen.
The project Detecta has hundreds of surveillance cameras from the police and public institutions and will be integrated with cameras from shops, residential condominiums, and private organizations. The police agents operating on the streets have computers that receive reports about suspects, robbery, crime, missing people, riots, protests, and once again, all the information is connected in digital networks of communication.

The eye of the State is becoming more present in daily life, with a more sharp view to observe what the citizens are doing, and eventually take action to restrain their rights. In the name of the order, of the security, and efficiency, it is consented that the privacy can be violated. And these issues are not only present in the government domain.

The polemic smart meter (of energy, water, and gas) is facing resistance, among other reasons, because it shares through a radio frequency network reports that could be recognized behavioral patterns, without resident’s permission, and also run the risk to have the energy hacked. Another example is the practice already common for auto loans is to use engine interruption devices, “technology that allows them to remotely disable a car” in case of missing payment [9]. Using a mobile telephone or web browser in a computer, lenders can track where the car is, its movement, and interrupt the engine with a touch on the screen. The car owners have to be submitted to these procedures otherwise they can’t get the car.
Antoni Martínez-Ballesté, Pablo A. Pérez-Martínez, and Agustí Solanas emphasize the importance of privacy on smart city because personal and sensitive information could be disclosed:

‘The fundamental rights of citizens should be guaranteed at all times. [...] Legislation is essential to guarantee the achievement of privacy within smart cities. Individuals must be aware of the ability of smart cities to silently gather a variety of information about them.’ [10]

Conclusion

It is comprehensive that technology could be used to improve the quality of life and of the built environment. But the fundamentals rights of the citizens should not be forgotten. The excessive control of everything under a script of surveillance should not be a part of a city that is intended to be intelligent.

The smart city concept brings the question about what is left from private space. It is an important topic that should be discussed by architects, urban planners and students. The wall in the architecture design that was meant to divide the private and public spaces is no longer sufficient to establish such differentiation of space. When one thinks about the IoT systems and devices there’s no boundary to avoid the algorithms search for private information.

The Internet of Things needs to be constantly criticized to ensure that the smart city is not about data collection to feed the surveillance systems. The digital networks of communications should be used to develop resources of creativity in the urban space. In this sense, architects and urban planners shall realize that the materials of construction in the smart city domain may be more than bricks and stones, but the focus of space design must remain on the people.

References


Hybrid connections
Computational mapping methodologies for Mexico City

Susannah Dickinson
University of Arizona
srd@email.arizona.edu

Abstract. The digital age is facilitating an ever increasing trend of globalized language and culture. Environmental issues are no longer a static concept as climate change and population growth force concepts of adaptability. What does this mean for the academy? How do we educate students to contemplate future urban scenarios and make some organization out of this more dynamic, complex future? The following paper seeks to disseminate a spring 2014 design studio at The University of Arizona where these issues were addressed, with Mexico City as a test bed. Computation has become a vital tool in the organizational process of these complex issues and big data. Various digital tools and platforms were explored in the studio to determine which ones would be most useful in modeling, mapping, designing and processing some of the complex relationships that are present in urban environments today.

Keywords: digital methodologies, urban design, complexity, hybridized networks, adaptability.

1 Introduction
Non-linear networks are central to the study of complexity in nature, with core disciplines in the areas of dynamics, information, computation and evolution.[1] Seeing our cities akin to living organisms that relate to the concepts of metabolic flows, self-organization and emergence are great role models for students to learn from. As humans have the ability to plan, think and design in a way that other forms of life cannot the design challenge today is to balance this ability for top down planning approaches, with some bottom up strategies that encourage adaptability in a more dynamic, humane sense. This implies the need to create hybridized, rich opportunities and design strategies that encourage increased diversity, on multiple levels, verses reductionist or top-down controlling solutions.

Globally there is a growing body of research relating to informal, more bottom-up communities as they become more pervasive across the planet. It is estimated that "by 2030, about 3 billion people, or about 40 per cent of the world’s population, will need
proper housing and access to basic infrastructure and services such as water and sanitation systems. [2] As research and definitions of informal communities develop, pre-conceptions need to be transformed. Positives of the informal sector are generally their economies, low ecological footprints and strong social structures with negatives being the lack of various infrastructures, public space and related health issues.

“It has been argued that the informal economy is neither good nor bad, it is simply a fact...a new knowledge of the city might emerge from a better understanding of the informal economy as a driving and determining force in major cities.” [3]

Mexico City is a great example of a mega-city, with multiple environmental, economic and social inequity issues. The city’s growth is predominantly informal with the informal economy counting for 60% of housing construction and jobs [4], but unlike many informal regions of the world, several areas are hybrids of formal planning with informal growth.

One of the goals of the following fourth year undergraduate, architecture options studio was to introduce students from more traditional, top-down planned, western communities to the global informal sector. This was in part a pedagogical strategy to explore more sustainable hybrid design solutions; embracing environmental, economic and social issues on a level that had been previously unconsidered.

1.1 Data visualization methodologies

The design process began with research and readings on contemporary urban design theories and methodologies, as none of the students had any previous knowledge or background in GIS or working at an urban scale. Later this research became more focused on Mexico City. The research was initially conducted from the United States, luckily with some fluent Spanish speaking students, with a physical trip planned for mid-way through the semester [5]. Students were allowed to work individually or in groups for the first time in a studio setting. The studio’s goal was to create design proposals based off the research, i.e. design as research. Intentionally, there were no prescribed design goals/limits at the outset of the studio, the pedagogical aim was to allow the analysis to dictate what the solution(s) should be i.e. it would emerge in a more bottom-up fashion directly from the specific research, hopefully in a more organic way than traditional design studio formats where a program and site are usually handed to students in a more top down fashion. This came from a desire to encourage more critical thinking and pro-active sensibilities from students; a necessary component today in a changing profession. It also seemed to mimic the complexity of urban conditions, that solutions could hopefully flow and emerge in a more bottom-up, self-organized way, with consultation from the top-down professor; a more team, hybrid teaching approach than the traditional autocratic one.

Simultaneous to the more theoretical research were assignments that allowed students the freedom and time to explore various digital methodologies that would help them obtain and visualize existing data on Mexico City. This step was crucial, although there are several required classes at the University of Arizona that teach
students various digital tools, there are no opportunities, prior to this class, where they are given official time to develop these skills in a studio design setting.

Today, as technology advances, there is an increasing emphasis on incorporating information and data into the design and analysis of the increasingly urbanized, built environment. Various ecological issues related to this shift have led to an increased desire for more performative smart cities and buildings and designs that focus on design drivers of behavior rather than pure form. “A second generation of digital architects and theorists are emerging who have placed an emphasis on open models of practice where the application of technology promotes technique rather than image.” [6]

Data visualization or graphics is a fairly recent phenomenon that if well-designed, can be “the simplest and at the same time the most powerful” means of communicating [7]. Edward Tufte speculates that the recentness of the invention is perhaps because “[of the diversity of skills required – the visual-artistic, empirical-statistical and mathematical” [8]. All of which are ideal traits for architecture students. Tufte continues to assert that “The purpose of an evidence presentation is to assist thinking” and that “Graphics reveal data. Indeed graphics can be more precise and revealing than conventional statistical computations.” [9-10]

Digital visualization tools are a necessary component of understanding these complex urban conditions. Ideally we would have a 3d digital model linked in a live way to endorsed data sources. What if this does not exist? How do we work with information in a smart way if we do not have easy access to it and a limited amount of time in a semester to get and process the data? Various cities and countries have different strategies to their information, some have web-sites with various open source information. USGS sites are often a starting point for projects in the United States, but what about the rest of the world, where information may not be so immediate or cities that do not want to share their information? The following spring 2014 studio researched this scenario with Mexico City as a test bed.

It soon became apparent that relevant and desired areas of data were not available in convenient GIS shape files with geo-tagged information [11]. This meant that research was needed into finding new methodologies and processes to visualize this disparate information in order to help with the design process. These initial studies and goals were about determining a strategically designed focus/site for the future project and/or proposal by understanding the existing. The methodologies discovered, on reflection, are also relevant for global sites with “smarter” existing documentation; as in this information age new sources and levels of data are continually becoming available to designers.

Initially one of the students, Cesar Rodriguez, looked at the growth and change of the density of the city over time [Figure 1]. Other census and environmental data was also researched, one of the best sources of data he found was in a published document with colored raster based image files [12]. Cesar initially created a matrix to overlay all the information against each other [Figure 2].
He realized he wanted a smarter way of analyzing these maps, beyond the visual, so he compared various ways of processing these images digitally. Initially he used the adobe software programs. Photoshop’s “Histogram Analysis” tool allowed him to see a range of color values within an image, which gave him a mean value for the various statistics. A further web-based analysis, called the “Image Color Extract PHP” allowed him to understand the percentage of pixels within an image that contained a specific color [13]. Both of these methodologies were slightly limited though, as they
were not relationship based i.e. they gave statistical breakdowns of the data, but one could not accurately analyze where specific information was located [Figure 3]. He was able to achieve this geographic relationship with the use of Rhino Grasshopper’s “Image Sampler”. Cesar created a script that related each color to various visualization tools. In the published example he recreated a concentration of circles whose diameter related to the geographic proximity of the color concentration. With this methodology multiple maps were overlaid to understand the proximities and/or main areas of interest. In this particular case he was looking for an area in transition from an informal to formal settlement [Figure 4].

Fig. 3. Digital methodology showing how raster based data could be analyzed and overlaid. (source: Cesar Rodriguez, B.Arch graduate 2015)
Fig. 4. Grasshopper tool: the size of the circle was directly related to the housing quality, i.e. larger circles designated more informal neighborhoods. The green area, Neza, shows the area selected by the student for further study (source: Cesar Rodriguez, B.Arch graduate 2015)

A student team, comprising of Joseph DiMatteo, Casey Kell and Joseph Mirandainitially created maps as a way of identifying trends in various census data. This process began with “Live Tracing” pdf maps in Adobe Illustrator to gain vector boundaries and layers that were imported into Rhino. They simultaneously developed a three tier approach to issues of importance, based on their readings, related to various socio-economic and environmental factors affecting human needs [14]. This was created to provide a hierarchy and focus for their mapping data [Figure 5].
Fig. 5. Diagram showing hierarchy of design issues related to sustainability (source: Joseph DiMatteo, Casey Kell and Joseph Miranda, B.Arch graduates 2015)

The rhino data was parametrized with grasshopper as a way of visualizing how neighborhoods had changed over time, by allowing parametric vectors to connect and show how geographical areas had physically moved and changed over time, utilizing the “Closest Point” grasshopper command. This enabled the fourth dimension to become part of this more dynamic, graphical equation. Ultimately maps were overlaid with each other and with other collected data relating to proximities of various infrastructural elements like water and transportation. This combined graphic database led the group to choose a site based on extreme diversity, they saw these as “tumultuous areas,” and the most opportune sites for implementing incremental change [Figure 6]. Even though these maps incorporated time into the equation, they were still two dimensional representations of two-dimensional data.
Hybrid connections - Computational mapping methodologies for Mexico City

Fig. 6. Top row shows maps of existing conditions, the bottom row creates parametric relationships in grasshopper from these conditions to show relationships and proximities over time. (source: Joseph DiMatteo, Casey Kell and Joseph Miranda, B.Arch graduates 2015)

High resolution Digital Elevation Models (DEM) of the site were found via NASA’s Shuttle Radar Topography Mission website [15]. Various open source tutorials were found on the web which showed how to create 3d topographical maps from this image based data, the most useful sites the students found were Harvard’s GIS manual and Ted Ngai’s “atelier nGai” site [16]. The data was extracted and meshed with Rhino and the freely available LandSerf tool [17]. Landserf was preferred, especially for large sites, due to the ease of issues related to memory management.

Fig. 7. Topographic maps for Mexico City created with Landserf software. (source: Joseph DiMatteo, Casey Kell and Joseph Miranda, B.Arch graduates 2015)

Computational methodologies and tools are improving daily, with traditional architectural educational environments often being in a position of playing catch up to other fields. Interaction and inter-disciplinary work has become a necessary norm to combat these complex demands. Unfortunately in this particular studio there were no official collaborations with other disciplines, but there were various arranged field trips to stimulate the work. One of these was to a newly created department on campus whose focus was computer information and art. Here students were introduced to other web-based programs and the Processing programming language [18]. One student, Dulce Arambula took on this particular challenge to create her topographic maps through this interface and to start using the $3^{rd}$ and $4^{th}$ dimensional capabilities of this software to design network connections. Nodes were placed in an environment which would connect when they reached a defined degree of separation; conceptually she saw these as representing walkability and public transportation. The topographic map was layered with geological information and future precipitation data to start a hypothesis on how future water decentralization strategies could aid in sustainable futures [19]. The concept was that this decentralization would leave the city less vulnerable in a crisis, such as an earthquake etc. The nodes would also relate to essential infrastructural elements beyond transportation such as water collection, food production and bio-fuel generation. Depending where the nodes were related to the geology below, they would also help to replenish the aquifer. All these designs and methodologies were presented in a live, animation format.
Finally, student Lisa Martinez used climate change data to select her site [20]. She selected the western region of Santa Fe in part due to this data and also for socio-economic reasons [Figure 10]. The area consists of geographical ravines that originally brought much needed water into the city from the mountains to the west. Projected data showed an increase of precipitation in Santa Fe, while decreasing in the rest of the city. Currently large parts of this area have become desirable, rich suburbs, with adjacent informal communities often pushed across or up the ravines in any available land, exasperating erosion and polluted run-off issues. This treacherous situation will doubtless increase with future population growth and rain.

Fig. 10. Projected future precipitation and vulnerable area overlay (source: Lisa Martinez, B.Arch graduate 2015)
Slope analysis was studied further using the Sonic plug-in for grasshopper [21]. It enabled Lisa to visualize how water would flow during rainstorms related to existing and/or proposed structures. Grasshopper was used to visualize the anticipated soil erosion related to these flows: the steepness of the slope and the degrees of curvature of the water paths were related to corresponding visual aids to emphasize these issues. This was also used as a methodology for anticipating how the water could be harvested, future positioning of buildings and relating hillside steepness to specific remediation and retaining strategies [Figure 11].

Fig. 11. Visualizing watershed and erosion (source: Lisa Martinez, B.Arch graduate 2015)

1.2 Findings

Map projections and distortions are a large topic in itself beyond the scope of this paper. It became clear that this differential in representation was an issue with the multiple sources of data that were found, but due to the large scope and hypothetical nature of the studio, this was not a major focus. Apart from mapping the more obvious forms of data, there were conscious efforts to make more invisible information visible, like pollution, future climate change, infrastructure below grade etc. This initial research portion was verified as much as possible when the studio visited the proposed sites in Mexico City. Apart from understanding the city fabric, systems and scale to another level, we were able to see issues that the virtual interface and remote location had not allowed. Traveling to the Centro de Abasto, the largest wholesale marketplace in the world, at 5am is hard to comprehend virtually [22]. We were also fortunate to meet with many local architects and urban designers who had more history and knowledge of the local issues including the leader of the new Urban Agency, Agencia de Gestion Urbana de la Ciudad de Mexico, Fernando Aboitiz Saro [23]. Here we saw the beginnings of their digital live information center and heard about specific concerns related to the City. Students were also able to present their project hypotheses and get feedback.

It was clear that this more research centric process, compared to typical architecture studios created a more emergent design process, where defining the problems and processes became more important than the solutions. Generally projects emerged that embraced the ideas of adaptability, agency and dynamism that the studio
had hoped to develop, with several students creating projects with elements of time and phasing, related to feedback loops into their final design proposals [Figure 12].

Fig. 12. Design proposal showing density network centered on transportation node, with aggregation logic diagrams over time to the top right.  (source: Joseph DiMatteo, Casey Kell and Joseph Miranda, B.Arch graduates 2015)

1.3 Conclusion

Although architecture cannot resolve all social and environmental issues, especially in a semester, it is imperative for students to be exposed to the complexity of global issues. With increasing pressures from Universities and Professional Accreditation Boards for performance standards, it is important to allow room for exploration that is less deterministic. Students reacted very positively to this freedom and to the ability to travel internationally. Fortunately this particular studio had no specific accreditation demands related to the course, but there was still pressure to perform and show a „product” at the end of the semester. Although this paper mainly focuses on the mapping methodologies, the design proposals that resulted were in most cases exciting, solution-based, relevant commentaries on our global precarious situation.
Big data and information is becoming more and more pervasive. Learning to be an active participant in this editing and software hacking process is key to ensuring the continued impact of designers on this creative process in our superficially more scientific environment. It is also imperative to understand that data, representations and software programs are not neutral entities. We need to understand the source of this data and the related ethics that may be in question [24]. Even though in this particular case none of the data was in the form of a live stream, there were creative ways of incorporating time into the design process to understand these issues in a more dynamic way, understanding that the model is always in flux.

This was the first studio that had a largely informal, mega-city, Mexico City as its focus. In part due to the proximity to Tucson, Arizona, it is hoped that this work will continue and be built upon to advance the knowledge and research in this increasingly important, complex area. Many of the mapping methodologies were also disseminated to lower level classes to aid in basic site acquisition information and modeling.

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This specific meeting was organized with the help of Jose Lever, the Director of the University of Arizona Mexico Office.
Urban codes

Abstraction and case-based approaches to algorithmic design and implications for the design of contemporary cities

Anastasia Globa\(^1\), Jules Moloney\(^2\) and Michael Donn\(^3\)

\(^1\)Victoria University of Wellington, \(^2\)Deakin University
globalnaya@gmail.com; jules.moloney@deakin.edu.au;
michael.donn@vuw.ac.nz

Abstract. This paper reports on a comparative study that evaluates two approaches to support the learning and use of algorithmic design in architecture, and extrapolates from this to consider applications for the algorithmic design of cities. The study explored two methods to reduce the barriers of using programming and potentially improve design performance. The first is the reuse of abstract algorithmic ‘patterns’. The second approach is the reuse of algorithmic solutions from specific design cases (case-based design). Reflecting on this research we outline how our findings discussed in relation to alternate thinking on the use of pattern, might inform a hybrid approach to the algorithmic design of cities.

Keywords: Case-Based, Design Patterns, algorithmic design, Urban Design

1 Introduction

The use of algorithmic design systems and programming environments offer architects immense opportunities but it can also impose considerable challenges [Menges, Ahlquist, 2011]. Fundamentally, programming logic does not relate to conventional design approaches in architecture such as, hand sketching, building physical models and manual CAD modelling. Traditionally, programming has not been a part of the architectural syllabus, but increasingly visual programming has increased uptake in design education and practice. Despite this relative accessibility, a procedural approach is required, which can be frustrating and cause many difficulties for both novice and advanced users [Celani, Vaz, 2012; Woodbury 2010]. Moreover it is not easy for some people to use programming algorithms when translating their idea into form. Many designers find it difficult to integrate algorithmic thinking and programming techniques into the design process [Woodbury, 2010], because the algorithmic logic of the idea-to-form translation introduces novel principles of design thinking [Matcha, 2007].

Algorithmic design is a discipline which belongs to the field of design, including architectural design, interior, industrial and landscape design etc. At the same time,
parametric design progresses through the use of programming. Consequently, it equally belongs to the field of computer science. The reuse of programs, algorithms and codes (software artefacts) is an important part of programming practice and research in the field of software design [Krueger, 1992]. Typically, these reuse techniques involve selection, specialisation and integration of artefacts, though the degree of involvement and the level of abstraction may vary depending on the reuse approach.

2 Testing Design Patterns and Case-Based Design

The study which forms the bulk of the paper explores and compares two distinct approaches as a means of accessing and reusing existing design solutions. The first approach is the reuse of abstract algorithmic ‘Design Patterns’. The second approach is the reuse of algorithmic solutions from specific design cases (Case-Based Design). The two methods of reusing abstract and case-based knowledge are not new. Over the past few decades, the pattern and case-based design approaches have been adopted by educators and practitioners in various fields of design, architecture and software development. While the methodology and principles of ‘abstract’ and ‘case-based’ solutions adaptation differ, both approaches seek to make reuse of algorithmic design knowledge more effective. The core of this idea is that design is not properly invention and creation of something absolutely new, but is rather a process of rediscovery [Terzidis, 2006]. Naturally, this rediscovery can be directly drawn from existing algorithmic CAD knowledge, inventions and solutions, because it is highly possible that someone, somewhere really did already invent the wheel you are about to reinvent [Mann, 2005]

2.1 Research set-up

The research was set-up as an experimental comparative study between three test groups: the group using Design Patterns, the group using Case-Based Design and the control group using no approach. A total of 126 designers participated in the study providing sufficient numbers within each group to permit rigorous studies of the statistical significance of the observed differences. The study was organised in the form of two-day parametric modeling workshops using Grasshopper for Rhinoceros. In each of the days, participants were given one design assignment, which they were to develop on their own, after an introductory series of exercises focused on familiarisation with the code and with the approach to design reuse. It was suggested that participants model and submit their designs within a two-hour period at the end of each workshop day. The collected data consisted of submitted 3D models, programming definitions and survey results.
2.2 The Level of Abstraction in the Reuse Approaches

To test the reuse of abstract algorithmic solutions in architecture, this study used the thirteen patterns for parametric design, developed and illustrated by Robert Woodbury [2010]. In his book ‘Elements of parametric design’ Woodbury states that designers who use parametric modelling tools tend to create algorithms anew, rather than reuse them [Ibid]. The idea of design patterns is that instead of solving each new problem individually, architects can reuse the generalised algorithms (patterns) of existing, successfully implemented in the past, solutions [Gamma, Helm, Johnson, Vlissides, 1994]. Patterns refer to the solutions, described with a high level of abstraction. This way design patterns can be individually interpreted depending on a particular design context. In Woodbury’s book and a website dedicated to the patterns for parametric design [Designpatterns, 2014] each of the design patterns is explained using the ‘Name’, ‘Intent’, ‘Use When’, ‘Why’ and ‘How’ and is illustrated by a set of samples (specific solutions), which are shown as a sequence of images.

The Case-Based Design (CBD) approach is based on the reuse of design solutions from specific design cases. In the context of this study the CBD approach refers to the reuse of algorithmic solutions in architecture. This approach was tested using an online data-base system, specifically developed for this study, which contained over one hundred fifty programming solutions. The primary purpose of these re-usable solutions was to help designers and architects to solve their own (similar) design problems [Maher, de Silva Garza, 1997]. In various fields, including architecture and software programming, the use of Case-Based Design approach proved to be an effective method, helping designers and developers to solve problems by reusing previous solutions and experiences [Kolodner, 1991][Aamodt, Plaza, 1994][Riesbeck, Schank, 2013].

3 Results. Decrease of the Programming Barriers

In many aspects, such as for example the ability to overcome programming difficulties, the reuse of abstract (Design Patterns) solutions is more helpful than the reuse of solutions from a case-base (Case Based Design). The use of CBD proves to be mostly effective in overcoming difficulties associated with the implementation of specific programming components and commands.

The diagrams in Fig.1 illustrate the overall amount of difficulties (the top diagram) and the typology and distribution of programming difficulties for each approach (the bottom diagram). In the diagram showing typology of difficulties the length of the pairs of bars either side of the central list of difficulties represents the percentage of workshop participants who reported each difficulty. The most common difficulty for people learning to use algorithmic modelling tools was the ‘Idea-to-Algorithm Translation’. It was reported as a problem for 43-60% of workshop participants. Even on the second day of the workshops when participants were more experienced in algorithmic modelling the number of issues with translation of a design idea into a programming algorithm was still very high.
The second most common type of difficulty was problems with actual implementation of a particular programming component: 21-49% of participants (Fig.1). The reuse of solutions from the case-base proved to be an effective approach to overcome these types of difficulties. There were significantly less problems with particular programming components in the CBD group, compared to both the DP and the no approach group.

Assigning a score of 1 for no difficulties, a score of 2 for 1-3 difficulties and so on to a score of 5 for 10 or more difficulties produced the three bars to the right for ‘No Approach’, ‘Abstract Approach’ and ‘Case Based Design Approach’. The average score (number of difficulties) on day 1 and on day 2 is significantly less for the reuse of abstract solutions (Design Patterns) approach. Reuse of abstract solutions is therefore an effective method to help designers reduce difficulties associated with use of algorithmic modelling tools. The DP group participants had significantly less programming difficulties compared to both the CBD and no approach groups. Despite this clear difference, it is worth remembering the case-based (CBD) approach did help to overcome certain types of difficulties (Fig.1).
4 Effect of the Approaches on the Design Thinking and Performance

4.1 Shift in Design Thinking

Compared to the control group participants (no approach), participants in both abstract and Case-Based reuse approach groups demonstrated improved performance. The differences in results were statistically significant (at 95% certainty level), including the ways designers’ think and perform; and in what they ultimately produce. One of the most statistically significant differences is the major shift in the design objectives, caused by the use of approaches.

The differences in objectives manifest themselves when designers gain more experience in algorithmic modelling. This can be seen in (Fig.2). It illustrates the measured differences in the design ideation criteria between the test groups on each day of the workshops. For three of these five criteria were the differences statistically significant: for these the p-value is highlighted in black, not grey. Interpreting the measured responses, we can see that those designers who reused abstract solutions (the Design Patterns group) were more focused on experimenting with parameters (Fig.2).

Participants of both approach groups were much more likely to explore algorithmic form-making and to try out new programming logics compared to the participants of the control group (no approach (NA)). It should be noted that the group using the Case-Based Design approach was also more invested in the investigation of the capacity of algorithmic modelling (46.8%) compared to the control group (24.4%), however the DP group showed the biggest interest ‘To explore algorithmic form-
making’ (63.3%) (Fig.2). Those who reused algorithmic solutions from specific design cases (Case-Based Design group) were more committed to realise the originally sketched design ideas and were less interested in explorations and experimentations (Fig.2).

The shift in design objectives and modelling priorities appeared to have a significant influence on the design process and, as a result, on the final design output. The test group who reused abstract solutions (DP group) were less committed to a particular design goal. This is illustrated in (Fig.3) by two designs from the DP group where the two participants reported a score of 2 (out of a maximum 5) on their ability to model their original design idea. The figure shows the original hand sketch and the output model from their Day 2 DP workshop. These two participants also reported a 4 (out of 5 again) on their ability to find a Design Pattern that fitted their idea and a 4 on their ability to accomplish what they wanted. As shown in (Fig.2), participants in this group were more likely to experiment and try alternative options of programming logic and components. This in turn has apparently influenced the way designers created their programming algorithms. Analysis of the programming algorithms showed that, those who reused abstractions had a significantly greater explored solution space of the algorithms, compared to the group who reused specific design solutions.

Fig. 3. Design Patterns group. Typical cases where designers have significantly changed their original idea and still reported that they were able to accomplish what they wanted.
Statistical testing indicates that designers who used case-based reasoning while developing their parametric solutions tended to focus on modelling a particular design outcome. They were less interested in exploring different programming options and new strategies. Instead, those who used CBD tended to implement components that they already knew (and which were explained during the workshop tutorials). When browsing the online case-base, these workshop participants predominantly used key words associated with already familiar (used in the past) programming components, rather than using abstract key words, thus reducing the likelihood of developing alternative programming solutions.

### 4.2 Change in Model Complexity

The evidence suggests that use of case-based reasoning in parametric design will most likely decrease the variety of programming components used to create algorithmic models. Designers who use CBD also tended to produce less novel (more typical) programming solutions. However, it should be noted, that while the CBD group did use a substantially smaller range of programming components and developed less novel programming solutions compared to both DP and no approach groups, they reported higher overall satisfaction with the design model and their ability to accomplish their design objectives than with the abstract approach.

The shift in design strategies caused by the use of abstract and case-based algorithmic solutions had a significant effect on the complexity of produced designs. Designers who reused specific programming solutions (CBD group) were likely to develop less complex output models, compared to both the abstract (DP) and no...
approach groups (Fig. 5, 6.). It would appear that the ‘abstract’ group’s greater interest in experimenting with forms and parameters produces designs less restrained by the limitations of the original design concept. Four example designs from this abstract group are shown in (Fig. 5, 6.). The score highlighted in black under each design has been developed as a means of systematically ranking the complexity of the programming algorithm. All four of the participants whose work is illustrated reported high (5 out of 5) satisfaction with their output model, but were far less satisfied with their ability to model their original idea (a score of 2 or 3 out of 5).

The no approach workshop group were like the DP group in that they showed greater readiness than the CBD group to change their initial concepts, and to develop and experiment with their designs. The CBD group participants were more likely to try and develop a particular programming sequence, which would generate the form that they originally sketched, even though this might prove to be time-consuming.

Correlational analysis was used to study the reasoning of the designers in each group. Higher complexity levels of the output models and of the programming algorithms are perceived positively by those who reused abstract solutions (Design Pattern (DP) group). The more complex the design models that DP participants produced, the higher is their satisfaction with the output (correlation coefficient 0.463). Those DP designers, who managed to develop more complex programming algorithms also found the DP approach more helpful (correlation coefficient 0.417). Model and programming algorithm complexity are seen by these designers in a positive light.

Fig. 5. Examples of models, designed by the DP group participants, who were able to accomplish what they wanted; significantly changed the original idea; and developed more complex programming algorithms and output models.
Fig. 6. Examples of models, designed by the CBD group participants, who were able to accomplish what they wanted; managed to model the original idea; but developed more simple programming algorithms and output models.

In contrast to the abstract DP group, designers who reused algorithmic solutions from specific cases (CBD group) preferred to avoid complexity and tended to settle for the more simple programming algorithms. On both workshop days ‘algorithm complexity score’ has a negative correlation (correlation coefficients -0.362 / -0.378) with ‘satisfaction with the design outcome’. When the CBD group participants managed to come up with more simple programming solutions, they were apparently more satisfied with the outcome. In summary, those who reused specific solutions saw complexity in a negative light, which is the exact opposite of what the group who reused abstract solutions tended to think.

4.3 Key Findings

The evidence presented in this paper demonstrates that the integration of knowledge reuse approaches, with learning and design processes, is beneficial. Both extremes of the knowledge reuse approach reduced barriers to using programming in design and improved design performance. Design Patterns developed by Robert Woodbury (an example of the abstraction reuse) proved to be an effective design support and learning method, significantly reducing learning barriers associated with the use of algorithmic modeling systems and programming languages. The use of abstract solutions (patterns) helps architects to understand and adopt algorithmic design methods better. Even though most of the participating designers and architects found the use of patterns to be less intuitive and less easy-to-use compared with the reuse case-based algorithmic solution, overall the pattern approach proved to be a more effective design support method, particularly at the initial stages of learning.
The use of the Case-Based Design approach (reusing specific algorithmic solutions) helps to reduce problems associated with use barriers (the implementation programming components and syntax), which often occur when designers know ‘what to use’, but do not know ‘how to use it’. However, the reuse of case-based solutions does not reduce the overall number of problems, and seems to discourage design exploration. It encourages more focused reasoning, oriented towards the realisation of the original design intention.

5.0 Some Implications for Conceiving the Parametric Design of Cities

While the methodology and principles of ‘abstract’ (DP) and ‘case-based’ (CBD) solutions adaptation differ, both approaches seek to make re-use of algorithmic design knowledge more effective. Reflecting on this research in the context of the theme of CAAD Futures 2015, we consider some implications for the next city. The use of abstract patterns for this study was directly informed by Robert Woodbury’s ‘Elements of Parametric Design’, which cites the seminal work on design patterns by Christopher Alexander. After a flurry of activity in the 70’s and 80’s Alexander’s approach to the reuse and combination of abstract design patterns has reappeared in recent CAAD discourse: researchers at TU Lisbon have directly referenced the principles of pattern language to develop a GIS based urban design tool; FelizOzel has examined the relevance of pattern language for Building Information Models [15]; while a position paper by Andersen and Salomon traces a genealogy of pattern thinking from Alexander to Gregory Bateson, to propose alternate ways to use patterns for design [16].

The design of cities is one of the most complex systems that architects and urban designers face, hence perhaps the interest in the use of a pattern approach such as those developed by Christopher Alexander. Seldom, however, are complete cities designed at one time by one group of designers. Rather the design of cities typically occurs over time, often with overlapping and contradictory master plans and transport systems. Moreover, in many cases typography provides a complexity in the third dimension that works against urban grids and other street patterns conceived in plan. These factors and the failure of some of the modernist urban patterns, such as the point blocks of Corbusier et al, have meant the use of patterns in architecture and urban design have a mixed reception for contemporary designers. How might a hybrid approach, which combines the processing capacity of the computer to utilize patterns with a more intuitive, responsive ‘case based’ approach, be conceived? Ouzel’s paper on the relevance of pattern language for BIM and the paper by Anderson and Salomon on pattern thinking will be discussed for the contrasting insights they shed on the potential of a hybrid ‘abstract – contextual’ approach to the algorithmic design of cities.

The focus of Ouzel’s discussion of Alexanders’s pattern language is to identify the difference between the adaptation of the idea in software engineering ‘to model real world objects in a value free, impartial way’. In contrast, at the object classification and structural levels Alexander embedded his experiences as a designer within the
patterns. Relating this back to the above study, following the precedent of software engineering Woodbury considers parametric design patterns as neutral chunks of code. By comparison, in the case based approaches to developing parametric models, the intent of the designer who generated the case is embedded to the point where any major restructuring of relationships is constrained. In the case of urban design, as briefly discussed above, the level of complexity and contextual variation precludes the tabula rasa implied by abstract patterns. Nor would the superimposition of case based precedent be useful, given the difficulty of major restructuring (as would be required by the new urban context). We could predict that neither approach would be easily applicable for the parametric design in an urban context. Ideally, a parametric design approach for urbanism would enable exemplar urban typologies to be accessed and adapted within an open set of abstract patterns. A hybrid approach, which would enable a designer to start with abstract patterns and embed these with design intent, through the integration of the existing context and as appropriate, the overlaying of urban exemplars. In this conception of the application of abstract and case based computation, the new city would be a subtle mix of old and new typologies tuned to specific contexts.

Anderson and Saloman take a wider perspective on pattern thinking, which provides an alternate take on how abstract and case based parametric design may be useful in conceiving the new city. Their critique of Alexander’s pattern language is that this privileged homeostasis, intended to maintain continuity and identity. They argue that this is at odds with the dynamism of natural and human systems (such as contemporary cities). They contrast Alexander’s pattern language with the dynamic conception of patterns by the chemist Ilya Prigogine. His research focused on forms of behavior that appeared chaotic but moved in and out of recognizable patterns. ‘From Prigogine we get an interpretation of the pattern as a condition of instability embedded in an entropic and unpredictable environment, rather than juxtaposed to it.’

Computationally this conception of pattern would map to a self-organizing system, such as that achieved by agent and flocking algorithms. Such algorithms underpin software used to model human movement through urban systems (space syntax) and traffic modelling applications. Agent approaches have also been used to generate urban form, although these appear to have minimal practical applicability to contemporary cities. Returning to a discussion of a hybrid approach to a parametric city design system, the precedent of Prigogine suggests the integration of form and patterns of use over time. One way to conceive this would be the identification of fixed and dynamic aspects of a model. Just as architecture is increasing responsive to changes in environment and usage patterns through dynamic ventilation, sunshades and access control, the future city is likely to have a level of automation. In conceiving the components of an urban parametric system, a distinction could be made between fixed and dynamic components. The dynamism would be at a range of temporal scales: real time (such as traffic control systems); components that respond in relation to daily cycles of light, weather and occupation (e.g. automated lighting, sun screens, access control); and seasonal cycles where for example, an open piazza becomes a winter garden.
This final section has opened up the study of abstraction and case based approaches in relation to the complexity of designing urban systems. The study provided evidence of how young designers respond to the introduction of abstraction and case based parametric design. The context or urban design reveals neither approaches would be directly applicable to such a complex design context. While parametric design offers promise, there is a much more research – both software development and studies of designers engaging with complex urban contexts - to be undertaken. Our next stage of the project will be to explore such a hybrid approach to parametric design as that outlined above and undertake similar rigorous evaluation of the uptake and impact on design outcomes in a more complex design context.

References

The potential use of laser scanner in urban contexts

Douglas Lopes de Souza, Andressa Carmo Pena Martinez and Denise de Mônaco Santos

Federal University of Viçosa
{douglas, andressamartinez, denise.monaco}@ufv.br

Abstract. 3D laser scanner is an instrument that employs LiDAR technology to map out objects in space by means of remote detection. In Architecture, digital mapping through 3D laser scanning mainly aims at creating digital surface models based on instant recordings of still objects, whereas lived spaces such as squares, streets, and urban surroundings presuppose the presence of people on the move. This paper presents some preliminary results of an investigation on the use of 3D laser scanning in urban contexts. It seeks to examine experimental data on moving people obtained in point clouds and discuss their operationalization possibilities and limitations. The main goal of this investigation is to assess the potential of this technology for use as a research tool and in city-scale design processes.

Keywords: 3D laser scanning technology, motion modeling, geometrical modeling, computational tools, urban survey.

1 Introduction

The use of digital technologies in architecture and urbanism has given rise to research on several fronts. Close examination of paths followed by today’s design and production processes indicates that fast prototyping devices, such as 3D printers and laser cutters, have had a huge impact on them, especially at laboratories of Architecture and Urban Planning programs. Moreover, their use can also be found beyond the academic walls for various purposes.

Different, however, are the features of LiDAR (light detection and ranging) technology, whose application to everyday processes is less common and still restricted to specific niches of expertise and whose potential is only now being widely explored by researchers and scientists. LiDAR is an optical technology that enables tracking and modeling objects in space through remote sensing, that is, to determine the distance, dimensional properties and/or other information about a distant object. The 3D laser scanner is one of the equipments that scans surfaces of objects by means of laser beams and promptly provides accurate data about their geometry.
Research aimed at the use of 3D laser scanning technology for mapping and creating a DSM (digital surface model) is being conducted in the fields of archeology, geomorphology, geomatics engineering, historical and cultural heritage preservation, geography, geology, forestry, remote sensing, and atmospheric physics as well as in the military context. It is different from other tracking and image-based modeling methods, i.e., photogrammetric processes or surveys with other equipment such as GPS (global positioning system). Studies employing 3D laser scanning technology aim at exploring its potential and improving its prospects of use in specific contexts, but, as it often happens with research designs that employ any given technology, investigations that use 3D laser scanners share some advantages and disadvantages inherent to this tool. Among the relevant advantages is its submillimetric accuracy in obtaining 3D geometries by means of automated fast measurement processes. One of the downsides is the price of this equipment, comprising the laser scanner itself and a computer capable of processing point clouds, which constitute the main graphic representation it provides. In addition, its operation is time-consuming since in spite of its digitalization process being fast, subsequent data pre-processing, which includes segmentation, grouping of point clouds, modelling, optimization, model edition, and exporting products in several formats according to proposed ends is work-intensive [1].

The applicability of technologies involving the use of 3D scanners in the field of architecture has been continuously improved as regards the scale of the object and/or building, especially in areas of historic preservation, as indicated by Gomes, Bellon, and Silva [2] and Fassi et al. [3], and more recently with digital scan-edit-print processes for various purposes. Notwithstanding, 3D scanning appears to have been little explored in connection with urban scale, especially when it comes to digital mapping and modeling of urban fragments to support design processes in the field of urban design. Urban spaces are lived spaces; they often presuppose the presence of people on the move. However, when employed to digitally map and model spaces such as squares, streets, and urban environments in order to collect information to support design processes on this scale, 3D scanning usually eliminates moving objects, for example, vehicles, bicycles, pets, and especially people, from the scenes.

This paper presents some preliminary results of an investigation on the use of 3D scanning on the scale of urban fragments, conducted atNoLab, a laboratory of the Architecture and Urbanism Department at Universidade Federal de Viçosa, Brazil. It depicts an experiment aimed at scanning a road closed to cars for exclusive pedestrian use downtown a mid-sized Brazilian city. The fact that this street has been closed to vehicles greatly improves the possibility of reading and systematizing data obtained by this means from the perspective of moving objects, as people.
The 3D laser scanning technology is almost exclusively suitable for collecting information and modeling static objects. Moreover, in the context of urban space, this modeling usually leaves out and/or segregates data on moving objects. In the face of that, two questions seem relevant: (1) In addition to providing location and size accuracy, what are the other properties of these data? and (2) What could architects gauge from the data obtained about moving objects, that is people, when operating a 3D scanner in urban spaces? This paper will initially examine these data in detail and then present some perspectives on and limitations to their operationalization.

2 Tracking Multiple People

Despite the existence of other equipment for observing and recording behavior in public space in the field of architecture and urbanism, such as, webcams, photos, behavioral maps, and more recently digital image fusion methodologies, most people-detection research is based on the analysis of motion video images due to its capacity for capturing a target individual’s shape and texture. However, high sensitivity to climatic conditions and camera angle limitations can greatly reduce instant accuracy of these methods, in addition to the difficulty in digitally combining data from multiple cameras, which requires a software program capable of integrating algorithms to graphic data for post-processing information adequately.

Several measurement methodologies of this nature have been developed in robotics and automation or computer vision and image understanding algorithms, which integrate algorithms to point clouds when using a 3D scanner for numerical count or identification of individuals in public open spaces [4-8]. However, a 3D laser scanner enables recording of various scenes irrespective of lighting conditions. It is not affected by variations in light conditions, and recording and pre-processing do not take much time. Moreover, a 3D scanner provides dimensional accuracy, exact location of people, distance between them, path speed and direction, among other geometric characteristics of scenes that can support urban design. According to Isaki and Helme [9], ‘in some of the early work, visualizations were used to reveal inherent geometrical properties of space, leaving it to the designer to speculate on and interpret the results, based on his or her knowledge and experience’.

2.1 Experiment

This experiment made use of the Z+F IMAGER® 5010C equipment (Zoller+Fröhlich), considered to be a terrestrial middle-range laser suitable for detection of buildings and scenes, unlike the short and long-range lasers used for scanning products and in planialtimetric surveys. It addresses the use of static LiDAR technology when equipment cannot be handled during data acquisition, differing from
operating a mobile equipment fixed on top of vehicles. A 3D laser scanner operates in active mode by gauging the return speed of laser pulses emitted by a target. The laser scanner employed generates a beam that can go 320 degrees vertically to detect what lies ahead and behind the equipment (horizontal capture of 360 degrees). This beam falls on a material and returns there by providing data to estimate the target individual’s distance from the difference of phase between emitted and received waves.

In this study, the evaluation of 3D laser scanner for detecting people was carried out in a real context, and involves two pedestrian streets. Although the equipment is omnidirectional, the axial spaces of the roads in question were chosen because of their potential for mapping circulation flows in addition to providing the benefit of a limited vision angle, initially set at 150º and later at 180º, which favored control of data generated by point clouds. No concurrent mappings were done, since that would have required at least two instruments and post-processing overlap of many point clouds.

Fig. 1 Axes indicate road and positions A and B of laser scanner during experiment.
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Table 1. Data regarding settings of point clouds resulting from captures at different resolutions for laser scanner positions A and B.

<table>
<thead>
<tr>
<th>Resolution</th>
<th>Lines</th>
<th>Precision (at 10m)</th>
<th>Time (min)</th>
<th>File Size</th>
<th>Points displayed (thousands)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position A</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preview</td>
<td>522</td>
<td>50.3mm</td>
<td>00:21</td>
<td>1.3Mb</td>
<td>223</td>
</tr>
<tr>
<td>Low</td>
<td>1043</td>
<td>25.1mm</td>
<td>00:43</td>
<td>4.8Mb</td>
<td>887</td>
</tr>
<tr>
<td>Middle</td>
<td>2085</td>
<td>12.6mm</td>
<td>01:25</td>
<td>16Mb</td>
<td>3563</td>
</tr>
<tr>
<td>High</td>
<td>4168</td>
<td>6.3mm</td>
<td>02:50</td>
<td>60Mb</td>
<td>14342</td>
</tr>
<tr>
<td>Position B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preview</td>
<td>626</td>
<td>50.3mm</td>
<td>00:25</td>
<td>1.5Mb</td>
<td>245</td>
</tr>
<tr>
<td>Low</td>
<td>1252</td>
<td>25.1mm</td>
<td>00:50</td>
<td>8Mb</td>
<td>990</td>
</tr>
<tr>
<td>Middle</td>
<td>2501</td>
<td>12.6mm</td>
<td>01:39</td>
<td>20Mb</td>
<td>3892</td>
</tr>
<tr>
<td>High</td>
<td>5001</td>
<td>6.3mm</td>
<td>03:19</td>
<td>77Mb</td>
<td>15372</td>
</tr>
</tbody>
</table>

At position A (fig. 1), the equipment was placed on a 6-meter high balcony. The 3D laser scanner was set to map a 153°-wide enclosed area and the system was tested at four different standard resolutions: preview, low, middle, and high, which produced several recordings lasting from 20 seconds to 3 minutes (table 1). It is well known that not only do these varying resolutions affect the quality and number of points that compose the clouds, but they also affect the scanner rotation speed during mapping. It was necessary to perform several captures at different speeds in order to improve accuracy of instant recordings of moving people and/or probable traces suggested by continual movement recorded by the scanner linear beams.

At the first position, the 3D laser scanner recorded above the pedestrian level, thus increasing both the distance between passers-by and the in-depth recording range. The intent of this oblique and high mapping in relation to the street axis at the ground level was to avoid possible data loss due to barriers created by people crowding in front of the equipment, although previous studies are based on data obtained at the time of the observer or on the level of ankles. As aforementioned, the equipment was positioned in such a way to capture recurring linear flows of people at an angle, which could favor captures parallel to the laser beams (Fig. 4).

At position B (Fig. 1), the scanner was placed at 1.8 meters above the pedestrian street crossing with the intention of recording flows both orthogonal and parallel to
the laser beam, thereby improving the mapping of intersecting flows occurring there. A 180° field of vision was thus selected, which allowed the recording of people’s paths in the main directions of flow on both streets.

3. Discussions and Results

3.1. People Recognition Distances

The distance range for capturing fixed objects with the equipment in question at a satisfactory level of element recognition, such as architectural elements, is approximately 160m. Although distances not exceeding 50m are recommended for conventional use to prevent decrease inaccuracy on millimeter scale, in this study, the maximum distance that the equipment managed to capture buildings was 170m. However, this distance was observed to drop considerably in the case of capturing people and to vary according to the chosen settings. As to the clouds recorded at position A, it was noticed that people could be recognized at high resolution at a maximum distance of 47.9m. At longer distances, it was not possible to identify passers-by accurately since the number of points was not large enough to enable distinguishing them from other elements in the scene (Fig. 2). The image in Figure 3 illustrates the maximum range of people identification based on close analysis of the point cloud at preview, low, and middle modes, whose recognition distances were 13.66m, 28.6m, and 39.14m, in that order. It should be remarked that this analysis implies approximating visualization within the cloud proper and carefully examining the patterns of points. Dispersion of these points over space, which typifies the recording of a moving person within a given period, is further discussed in 3.3 below.
Fig. 2 Analysis of patterns of points enables recognition of people. Image of point cloud showing the farthest person recognized at high mode at position A.

Fig. 3 Maximum recognition distance at standard resolutions preview, low, middle, and high at position A.
3.2. Recording of Moving People

Although previous studies used the laser technology to quantify pedestrian groups in an event, this paper analyzes the recording of moving people in a public space. It was identified that the pattern of recording people on the move depends on the combination of two variables: position of laser beam relative to their paths and speed of flows over space vis-à-vis capture speed, provided by the adopted resolution. In other words, people recording patterns in a point cloud are directly linked to people’s path and their speed as compared to the scanner position and capture speed.

Two recurring situations may be identified in the recordings: people’s paths perpendicular to the scanner rotation path and people’s paths orthogonal to the scanner capture axis (frontal). When people cross the scanner-captured ‘scene’, that is, when their path is perpendicular to the laser beam, the point cloud will record the exact moment of intersection. In this case, there are two variables interfering with mapping results: their movement direction and speed. The scanner rotation is always clockwise in that pedestrians whose path is counter clockwise will be recorded as line fragments. However, when their movement is clockwise, they will be recorded as traces as shown in Figure 4. In these cases, the closer the pedestrian’s speed is to that of the scanner, the longer the trace is. Notwithstanding, it should be remarked that in both directions, an individual’s speed that is higher than that of the scanner will be recorded as line fragments in the point cloud. In the case of paths orthogonal to the scanner capture axis, regardless of their direction and coinciding with the equipment rotation or not, people are recorded as accurately as static objects are, the quality of register in the point cloud being affected only by the adopted resolutions.

Figure 5 shows several identified recording situations: highlighted in yellow is the trace of a path in the same direction as that of the scanner rotation at a speed close to the rotation speed; in orange are fragments of people whose paths were perpendicular to the scanner laser beam at higher speeds than that of rotation; whereas in red are recordings of people whose paths were orthogonal to the laser beam, which provided the largest number of data in the point cloud and, as a result, the most accurate identification of the human body shape.
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Fig. 4. Recording of a pedestrian’s path walking in the same direction as that of the laser scanner rotation (clockwise) as compared to people in a static position (position A, high resolution).

Fig. 5. Different recordings of people in a point cloud (position B, high resolution).
3.3. People Identification in a Point Cloud

Identification of objects in a point cloud is linked to the density in space of points that determine shapes-surfaces in a given period of capture. One of the ways of distinguishing static from moving objects is by juxtaposing densities of the set of points, especially when some sets only feature line fragments or traces, as mentioned above. For instance, architectural elements are more easily identifiable in a cloud because they provide dense sets of points determining their surfaces, which can be promptly perceived by the laser beams falling on them repeatedly. On the other hand, moving objects are only subject to detection for a very short period of time. As previously shown, the type of recording of passers-by that cross the laser beam transversally cannot produce dense structure-shaping points — just line fragments or traces, irrespective of the adopted resolution. Besides, another way of identifying moving objects is to gauge the position of the sets of points in space—however scattered they may be—by measuring distances in relation to static objects.

At any rate, it is difficult to identify people in a point cloud when there is recordings of the line fragment type are close together. Two very close fragments may indicate the existence of two people walking side by side or just one person’s trace. In this case, there more be more research on accurate ways of identifying the number of people. In any case, juxtaposing densities and verifying the positions of points in space by assessing them in relation to static objects can promote identification of moving people in a point cloud.

4. Future perspectives

Most research conducted in the field of Architecture and Urbanism that employs a 3D laser scanner focuses on preserving cultural and historic heritage. Case studies comprise the majority of research designs and depict the constant development of this technology. On the other hand, there are fewer studies experimenting with this technology beyond its use to capture data on buildings, objects, and urban spaces with the intent of building accurate models. In this study, the use of 3D laser scanners presupposes a specific type of recording, that is, the instant recording of as till object. Therefore, it seems difficult to dispute the argument advanced by Shaw & Trossell [10], that ‘digital versions of space will always be just that – exact lists of numbers, of x, y and z values, the experiential properties lost as pure data’. However, in the context of this study, which investigates how 3D laser scanning and moving objects/people are related, it also seems pertinent to agree with the same authors when they claim that ‘Scanning offers these challenges to designers. If a digitized version of
space is uncanny yet cannot compete with the real, how can it enhance it, provoke it, change the way it is used?’ [10].

In this sense, this study provides questions for further research: Could data on people collected by means of a 3D laser scanner add informational or methodological perspectives to conventional processes and equipment for data collection and presentation of a given urban fragment? Is it possible to change the settings of a laser scanner so as to adapt it to register people in interaction with a given space? Is it possible to use these data as parameters to support design processes involving parametric digital modelling as well as generating processes?

Studies of this nature seek to explore mechanisms of 3D laser scanning technology as another tool for analysis of lived space so as to enable parameterization of traces of human relations and interactions in a given context. Apprehending this information can have repercussions to how the built environment is regarded, thereby contributing to design processes novel ways of dealing with people-dependent variables - their behavior and interactions - in space-time.

References

Augmented reality
Recognition of multiple models simultaneously

Ana Regina M. Ciperschmid¹, Regina C. Ruschel² and Ana Maria R. de G. Monteiro²

¹University of São Paulo
fale@anacuper.com
²University of Campinas
{ruschel, anagoes}@fec.unicamp.br

Abstract. The problem at hand is to ensure that the perception by means of Augmented Reality (AR) is hence reliable and opinions resulting from a Participatory Design (PD) mediated by this technology could be incorporated into the design solution. This paper presents the evaluation of multiple 3D models recognition in AR, with or without an auxiliary projection. Leisure area designs involve urban equipment of various dimensions that are visualized simultaneously. Therefore, it was necessary to verify if the participants were capable of recognizing them and which would be the best way to visualize: exclusively with the iPad screen or with the iPad associated with an external projection – to verify whether the visualization using an external projection would amplify the visualization area. The results obtained in the evaluation were used to improve the AR application and also, to develop guidelines for the AR use in a PD.

Keywords: Augmented Reality, Recognition, User Experience Evaluation.

1 Introduction

At the social housing Campinas F, in Campinas, SP, Brazil, there is a central area intended to be a leisure area for the neighborhood. However, this area was completely abandoned after the conclusions of the constructions of the buildings in 2006. To plan a suitable leisure area, a Participatory Design (PD) process using Augmented Reality (AR) was proposed. This article presents an evaluation of AR in order to be applied in the design process studied. The evaluation is in terms of user perception with AR, augmenting an abstraction of the real world, that is, a map or a design sheet on tabletop. In [1] mixed realities scale, this study can be characterized as of Augmented Virtuality.

In order to use mobile AR in the intended PD dynamic, the application equipAR! for iPad was developed. The purpose of this application was to enable the visualization and interaction on a tabletop in AR of 3D models of urban equipment for leisure areas. The idea was to use this application in the context of PD, involving

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users of multiple profiles, from architects to users. Users were members of low-income families, who often have little education and do not have familiarity with new technologies.

A leisure area includes multiple equipment; therefore, it was necessary to verify if the participants were capable of recognizing these equipment simultaneously and which form of visualization would be best: exclusively with the iPad screen or with the iPad associated with an external projection. The goal was also to verify if the visualization through the tablet screen presented restrictions of visualization in AR for large areas representing the urban space and whether, in this case, the simultaneous visualization using an external projection would extend the visualization area.

The equipment is visualized and manipulated through AR simultaneously in the PD process. This illustrates the problem at hand, which is to ensure that the perception by means of Augmented Reality (AR) is hence reliable and opinions resulting from a Participatory Design (PD) could be incorporated into the design solution.

2 Related research

Currently there is limited understanding of human experience with mobile AR, especially studies concerning Architectural, Engineering and Construction (AEC) applications. Many authors agree that research in emerging fields, such as AR, cannot base themselves on traditional directives to evaluate the interface with the user [2,3,4,5]. Little formal research, such as this one, has been performed to evaluate AR interfaces involving users [3], since AR systems differ from desktop systems in various aspects; the most crucial is that such systems are produced for being used as a mediator or amplifier of human visualization [2].

One interface of AR includes the hardware (e.g. smartphone; notebook), the software (e.g. Junaio, Layar, Wikitude), the devices for visualization (i.e. HMD, computer screen), the interface elements (e.g. menus, icons), the markers, the interaction format (i.e. rotating the marker, moving the remote control), and the content shown in AR. Depending on device, the tracking form, the interaction technique used, the interface in AR is altered. These factors may justify, in part, the lack of successful methods to evaluate AR interfaces.

According to [3], most AR user evaluations fit into one of the four categories: (i) human perception and cognition; (ii) user task performance; (iii) collaboration between users; (iv) system usability and system design evaluation. Among the research that study human perception and cognition, it is possible to mention a few related to this, as in [6, 7, 8, 11]. The research of [6] compares the use of tangible and graphic interfaces. Among the conclusions, the authors state that the understanding of spatial relations of virtual models is improved with the use of tangible interfaces. The research of [7] involved the experiment to verify which mechanism is more appropriate to visualize a virtual model: by the rotation of this model or by the observer’s move. The conclusion suggests that the user’s move updates the mental representation, producing a positive effect in the performance of virtual models.
recognition.

[8, 11] use mobile AR application to support public participation in urban planning. [8] developed a prototype smartphone AR system that superimposes virtual 3D models over an existing building and allows users to provide feedback based on their personal preference of the proposed designs. Their objective included the study of the public reaction to this technology, focusing on mobile device familiarity, system ease of use, and the system utility to participate in the urban planning project. The system was considered useful to participate in the urban planning project, suggesting that the system did not require a high level of technological familiarity to understand its purpose and utility.

[11] performed a user evaluation on the usefulness of a mobile AR system to visualize urban plans of an area to be reconstructed in Raseborg, Finland. The AR system used real sized models of the planned buildings in loco, stimulating a better comprehension of the proposed plans for the built environment. They focused on a qualitative research on perceived usefulness and ease of use of the system. AR was considered a useful instrument to visualize building plans in a holistic and intuitive way, facilitating the decision-making process and enriching the understanding of the plan.

The system designed by [8] uses a smartphone to superimpose 3D models to real buildings and the system used by [11] uses a smartphone to add 3D models of future buildings on a proposed area, while equipAR! uses a tablet to superimpose 3D models to markers, showing scaled models on a tabletop. Therefore, the purpose of equipAR! is not only to allow users to share common experience of design but also to allow participation in design by handling tangible AR elements and positioning them on an image of the space under design. In [11] the system was evaluated by decision makers - mostly city officials and members of the municipal government. On the contrary, this particular research is based on a different target user group, in which many participants did not have schooling at all and had never touched a mobile device before. While the overall purpose of this research is similar to [8, 11], the combination of system functionality, participants profile and user evaluation setup, makes this research unique, reinforcing the need for further investigation.
3 The evaluation

In this evaluation, the recognition of multiple models disposed in leisure area layouts were verified, associated to different forms of visualization (iPad screen with or without external projection) or participant mobility (with various angles of visualization). These issues could directly influence the dynamic of a Participatory Design (PD) with the use of RA. To proceed with the evaluation of multiple models recognition simultaneously, first, it was necessary to certify that the participant would recognize each of the urban equipment individually. In order to be able to measure these issues exclusively, a routine to guarantee individual correct recognition of each model was incorporated in the user evaluation.

The studies of human factors allowed us to establish a limit to the number of models of urban equipment exhibited. According to [12], the representations of the models seen sequentially are stored in the short-term memory; it was then reasoned that the study of visual recognition of multiple virtual models in AR should consider the limited capacity of this memory. This way, [13] recommendation for seven chunks of information was taken into account; therefore, seven different types of virtual models of urban equipment for leisure areas were used.

Given the fair recognition of the equipment in the scales of 1/100 and 1/50 - obtained in previous evaluation [9, 10] - and the preference for a smaller scale to discuss the leisure area project, the scale 1/100 was adopted to perform this evaluation. As the results of the previous user evaluation [9, 10] pointed to the preference of using fiducial markers, those were also adopted in this evaluation.

A second version of the equipAR! application (iOS) was developed, containing seven fiducial markers associated to seven virtual models of urban equipment for leisure areas in the scale 1/100 (Fig. 1), that is: a soccer field, a skate course, a multi-purpose sports court, an open-air gym, a playground, a set of tables with seats, and park benches. In this version of the equipAR! application, all the models were added with a neutral base to block the visualization of markers in AR, in order to avoid visual conflict, according to the need pointed out in previous user evaluation [9, 10].
To perform this user evaluation, the method described by [3] of subjective measures to evaluate the recognition was used. The evaluation was performed with non-specialists, individually.
4 Evaluation plan

The procedure to perform this User Experience evaluation was followed in phases, and performed according to the flowchart shown in Fig. 2.

(A) Presentation, characterization, and training

This phase would be comprised of three moments: a) presentation of the equipment; b) characterization questionnaire of the participant and c) training/learning. At first, the presentation of the equipment to the participant was performed, explaining the objective of the evaluation and the application’s function. Then, characterization questionnaire of the participant was applied, checking the age, gender, education level, the frequency of smartphone or tablet use and the previous use of any AR systems.

Finally, training or learning session was performed. To proceed with the evaluation of recognition of multiple models of urban equipment of leisure areas simultaneously, it was first certified that the participant would recognize each of the urban equipment individually. It was asked if the participant recognized each one of the seven models used in this evaluation. Then, each one was displayed the models in AR and asked, “What is this? - taking note of everything the participant could recognize. If they could recognize all, then they would move on to Phase B. If not, each of the urban equipment should be presented individually to the participant in AR until there was a guarantee of correct recognition. When identifying all correctly, the participant would be able to proceed to Phase B otherwise the evaluation would end.
(B) Recognition of multiple models: iPad in a fixed position

On a table with a white base seven fiducial markers would be displayed in three different layouts (Fig. 3). Different people would visualize each layout, individually. To verify if the leisure equipment of larger dimension interfere in the recognition of the ones with a smaller dimension, the ones with a smaller dimension would be positioned surrounded by the ones with a larger dimension, Layout 1. To verify if the leisure equipment of smaller dimension would be more easily recognized if positioned at the extremity and in the front, Layout 2 was configured. To verify if there would be any difficulty in recognizing when the leisure equipment of smaller dimension was positioned separately at the extremities, Layout 3 was configured.

![Fig. 3. Three kinds of layout of urban equipment in AR –markers positioned on a tabletop(up) and models of urban equipment seen in AR (down).](image)

Initially, the participant visualized the scenario in AR from a fixed position. For that, the iPad was set on a tripod with the camera directed to the table with the application equipAR! active. At this moment, the models of urban equipment of leisure area could be visualized in AR in scale 1/100.

Then, the researcher pointed and asked whether the participant was able to say which equipment was indicated. On a printed sheet, with a map of the equipment layout, the researcher registered whether each one of them was recognized. If all were recognized, the participant performed Phase C. If not, the evaluation would move on to another procedure; however, since it was not necessary to perform it, it was omitted.

(C) Visualization Preference

The purpose of this phase was to verify the visualization preference of the participant: the iPad on the tripod, the iPad on the tripod with an external projection, the iPad
Augmented reality - Recognition of multiple models simultaneously

being held by the participant with the option of mobility, the iPad being held by the participant with the option of mobility and external projection. To conclude, the participant was asked to say which was the best way to visualize all the set: with the iPad on the tripod, the iPad being held on the hands, iPad with the external projection on the tripod or the iPad with external projection being held by the hands. The researcher took note all the answers. Then, the evaluation continued on to Phase D.

**(D) Assess the quality of the participant’s experience while handling and visualizing in AR**

The purpose of this phase was to verify the quality of the participant’s experience when handling and visualizing in AR in a way to compose the leisure area. For that, each participant was asked to compose the leisure area with the available equipment in the application equipAR! Each participant performed one of the following tasks: (i) compose a leisure area for children; (ii) compose a leisure area for young people; (iii) compose a leisure area for the elderly. Each one had about 10 minutes. The participant could opt for a visualization form: with the iPad held by the hands or on a tripod, with or without external projection.

During the process, the researcher observed and noted how the participant performed the task: the visualization form and the difficulties found. Besides, the participant was asked to talk about the impressions, difficulties and opinions about the use of this technology. The researcher took notes and registered the process with photographs and video for further analysis.

At this phase, the quality of the interaction with the system was evaluated; therefore, the method proposed by [14] was adopted. [15] and [14] suggest that experiments that aim to evaluate cognitive performance be the most indicative of the user experience with the interface and, therefore, subjective measures or qualitative analysis should be adopted. In this situation, participants are usually asked to perform specific tasks. The biggest advantage of using tasks is that they tend to be more similar to the actions that users would perform with the system. Therefore, the acquired information with the cognitive performance evaluation tends to be more relevant and precise about the use of the application.

In this sense, [14] describes some categories of User Experience that can clarify user interaction with AR services. These categories are classified into six classes that represent subjective levels: (1) instrumental experiences, (2) cognitive and epistemic experiences, (3) emotional experiences, (4) sensory experiences, (5) motivational and behavioral experiences and (6) social experiences. These categories of User Experience should be used to perform measures in a qualitative evaluation. According to [14], measures may structure the evaluation process, supplying information that is comprehensible and subject to comparison, and may favor solution restructure.

In the adopted method, the User Experience evaluation is classified according to determined characteristics and graded with the Likert scale. The use of quantitative metrics of subjectivity allows for a better validity of conclusions and generalizations[14]. Therefore, at the end of the task of composing a leisure area with the use of AR system, each participant answered a questionnaire as shown on Table 1.
For all the statements, the participants marked one of the alternatives: Totally agree / Agree / Nothing to say / Disagree / Totally disagree.

The statements 1, 2, 3, 4 and 5 are related to instrumental experiences, which are the pragmatic experiences originated from the utility of the system (suitable to the proposed task), performance of the product, support to the participants activities, difficulties of interaction. The statements 6, 7, 8, 9, and 10 indicate the quality of the subjective emotional experiences originated from the use of equipAR!, such as pleasure, entertainment, and positive values of feelings. The statements 11 and 12 intend to verify the quality of the sensorial experiences. The statements 13 and 14 are related to the motivational and behavioral experiences, which are created when the participant is inspired or motivated to reach one objective with the help of technology.

Table 1. User Experience evaluation questionnaire. Statements based on [14]

<table>
<thead>
<tr>
<th></th>
<th>Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The experience of trying to compose a leisure area using Augmented Reality was easy.</td>
</tr>
<tr>
<td>2</td>
<td>The way to interact with the urban equipment in Augmented reality was natural to me.</td>
</tr>
<tr>
<td>3</td>
<td>When I used the Augmented Reality system I felt pleased for having a good performance</td>
</tr>
<tr>
<td></td>
<td>doing and concluding it.</td>
</tr>
<tr>
<td>4</td>
<td>I feel that using the Augmented Reality system is appropriate to the proposed task</td>
</tr>
<tr>
<td></td>
<td>(Composition of a leisure area).</td>
</tr>
<tr>
<td>5</td>
<td>The Augmented Reality system had the urban equipment I wanted.</td>
</tr>
<tr>
<td>6</td>
<td>I felt surprised when using the Augmented Reality system, it was a novelty.</td>
</tr>
<tr>
<td>7</td>
<td>I had fun while using the Augmented Reality system.</td>
</tr>
<tr>
<td>8</td>
<td>I felt I was discovering things while using the Augmented Reality system.</td>
</tr>
<tr>
<td>9</td>
<td>Using the Augmented Reality system was lively and dynamic, allowing for continuous</td>
</tr>
<tr>
<td></td>
<td>changes in the organization of the equipment.</td>
</tr>
<tr>
<td>10</td>
<td>I enjoyed the experience of trying to compose a leisure area using Augmented Reality.</td>
</tr>
<tr>
<td>11</td>
<td>I felt the desire to keep going while using the Augmented Reality system.</td>
</tr>
<tr>
<td>12</td>
<td>I was able to express my ideas for the leisure area using Augmented Reality.</td>
</tr>
<tr>
<td>13</td>
<td>I felt encouraged and motivated to conclude the task while using the Augmented Reality system.</td>
</tr>
<tr>
<td>14</td>
<td>I felt myself creative when composing the leisure area while using the Augmented Reality system.</td>
</tr>
</tbody>
</table>

Fifteen non-specialists participated in this evaluation.

5 Pre-test

To validate this user evaluation, a pre-test with seven participants was performed at the Laboratory of Architecture, Methodology of Project and Automation (LAMPA), located at the FEC building, UNICAMP. All the participants were students of the Post graduation Program of Architecture, Technology and City of FEC. It was observed that the participants had facility in recognizing the urban equipment individually as well as in a set, even when seen from the iPad screen only (Phase B). Therefore, a need was noticed to verify which would be the preference of visualization even in the situations where there is no difficulty in recognizing the set of equipment seen
only from the iPad screen. Thus, Phase D was added – not previously elaborated – that intended to compare the various forms of visualization: iPad fixed or mobile, with or without external projection.

During the task development of composing a leisure area, most of the participants opted to let the iPad on the tripod and visualize through the external projection. All of them were able to compose a leisure area using this technology.

6 User Experience Evaluation

To perform this evaluation it was necessary an environment with the following characteristics: wall or screen for projection, electric power for the projector connection, a table for displaying markers, leveled floor for positioning the tripod, protection to avoid the incidence of direct light on the markers (which would make it difficult for the detection of these markers by the AR system). Since the Journalist Roberto Marinho School was located next to the social housing Campinas F, it was necessary to ask for an authorization for the evaluation to take place in its facilities. The teachers’ room was made available in a full-time basis for this evaluation that was performed in March 2014.

The evaluation involved fifteen participants, among which, users or residents from the social housing Campinas F. Five people at a time performed the evaluation with a distinct task (compose a leisure area for children, young people and elderly).

6.1 Participants characterization

Nine participants were male (60%) and six were female (40%), Fig. 4 (left). The age group of the participants varied from 11 to 60 years old, Fig. 4 (right).

![Gender and Age Group](image)

**Fig. 4.** Participants’ gender (left) and participants by age group (right).

The education level of the participants varied, being five (33%) of them with a university degree and one (7%) who did not complete primary school, Fig. 5 (left). If compared by age group, out of eight participants over thirty years old, four had completed primary school, one high school, and three had university degrees. When asked about the frequency of use of smartphone or tablet, five (33%) were using it for the first time, four (27%) rarely use it or at least used it once, and only three (20%)
use it daily, Fig. 5(right). None of the participants had a previous experience of any kind of AR system.

![Highest educational degree](image1)

![Smartphone/tablet usage](image2)

**Fig. 5.** Participants’ education (left), Smartphone/tablet usage (right).

### 6.2 Results

Initially, the participants should recognize the urban equipment individually in AR. All the equipment was recognized without the need of training. However, in three situations it was necessary the researcher’s intervention in order to assist the use of the iPad searching for angles of vision that favored the recognition. The equipment that was recognized with difficulty was a table with seats and the open-air gym.

Then, the participants saw the set of equipment through only one angle of vision: iPad fixed or mobile, with or without external projection, Fig. 6. When the participant was asked about the visualization with or without mobility, without projection (graph A), seven (47%) preferred holding the iPad and moving around, two (13%) preferred leaving the iPad on the tripod, and six (40%) enjoyed the two forms, for they completed each other.

When the participant was asked about the choice of visualization without mobility, with or without the aid of external projection (graph B), six (40%) preferred only the external projection, five (33%) preferred the two forms together, and four (27%) preferred only the visualization from the iPad screen.

When the participant was asked about the choice of visualization with mobility, with or without the aid of external projection (graph C), eight (53%) preferred to visualize only through the iPad screen, two (13%) from the external projection and five (34%) enjoyed the two forms.

Finally, the participants were asked which would be the best form to visualize all the equipment once (graph D); seven (47%) preferred the iPad mobile with the external projection, five (33%) preferred the iPad fixed with the external projection, two (13%) the iPad mobile and one (7%) preferred the iPad fixed. If the choices that include the external projection as one of the forms of best visualization of content in AR are added, there are twelve (80%) that consider the use of external projection important.
During Phase D the participants were asked to set a leisure area with the same equipment used in this evaluation. The participant could choose the equipment most suitable for the task, i.e., compose a leisure area for children, young people and the elderly. Each participant had the freedom to choose the most suitable visualization form, being able to modify it during the task performance, as wished. Fig. 7 shows some participants at the moment of elaboration of the leisure area and the final result of the compositions.
During the execution of the task to compose the leisure area using AR, it was registered how the visualization occurred most of the time. It was observed that twelve (80%) of the participants used the iPad in a fixed position together with the external projection and three (20%) participants used only the iPad mobile without external projection, Fig. 8. The three participants who opted to use the iPad mobile without external projection had a familiarity with the use of mobile devices (using it daily or once or twice a week). When asked about the choice, the answer was: “It is the custom; I am used to moving and seeing the same screen”; “This way is easier, I see what I am doing right (in relation to the point of view being the same of the iPad)”. 

After performing the tasks, the participants answered a questionnaire (according to
Table 1) to evaluate the quality of the experience of the system usage, taking into consideration the task performed. It is possible to observe that, in general, the opinion about the experience was positive, Fig. 9.

Fig. 9. Results of User Experience evaluation questionnaire.

7 Discussion

7.1 Leisure area layouts and the recognition of multiple models

The recognition of three sets of leisure area composition was always positive, even when using only the iPad, without external projection. Therefore, the leisure equipment of larger dimension did not interfere in the recognition of the ones of smaller dimension. It is important to say that the chosen angle for static visualization did not cause occlusion of any equipment.

Therefore, when visualizing three different layouts, through the iPad fixed on a tripod, the participant was able to associate the equipment that had been recognized individually to the ones that were being seen on the iPad screen. In other words, thanks to the phenomenon of the shape constancy, described by [16], the previous individual recognition allowed the participants to memorize the equipment’s shape and, lately, even with the angle variation and distance, it was possible to recognize all of them.

This question was highlighted by the verbalization of some participants who stated: “I know that tables are round because I saw them before, the park benches too. The other equipment is really the model that we have in mind. Like the children’s playground, it is very colorful”; “As I could individually see before, now it is easy to understand”; “I only know it is a Gym because I had seen it standing alone, it is the most confusing”. The conclusion is that the models of equipment that have a small dimension, such as the park benches, or comprised of devices of a small dimension, such as the open-air gym, are more difficult to be seen as a set and need a previous recognition to be used. At this moment, the ones that chose to visualize using only the iPad screen pointed out that the colors were more vivid and the definition was better in this situation – factors related to the quality of the iPad’s image resolution. To express
this question, some phrases were mentioned, such as “The color stands out”; “There is more definition on the iPad screen”; “Here (pointing to the iPad) there are more details”. The ones who preferred to visualize using the external projection said “it gets larger in the projection”. This option was chosen by the participants who had some kind of visual impairment and verbalized it: “I am without my glasses, so seeing it on the wall is better (referring to the projection); “I am getting old, with a tired eyesight, so I prefer there (in the projection)”.  

7.2 Forms of visualization and participant mobility

All the participants were able to conclude the task of composing a leisure area using AR. However, it does not mean that they did not have difficulties, since some of them had no familiarity with the use of mobile devices and were over 41 years old. These people were insecure about holding an iPad to visualize and handling the markers.

One example of the difficulty can be demonstrated by the sequence of photos shown on Fig. 10, in which one participant tries to organize the leisure area positioning the markers on a table, without considering the dimensions of the equipment. At first, the user picked the markers one by one, turned it over, visualized by the projection and chose the set of equipment she wished. Then, she positioned markers on a table, without visualizing the result in AR. When she saw in AR the result of her composition, she said: “Oh! It is on the... Oh...!” The researcher asked her, then, to try to organize the equipment without composing one on top of the other. In the end, the user was able to elaborate the leisure area according to her wish.
Augmented reality - Recognition of multiple models simultaneously

Some participants felt the need to previously identify the leisure equipment to be used. This was verbalized as follows: “How am I going to know who is who?” “Are there names behind the markers?”. Such comments showed the need for the inclusion of a brief textual description to facilitate the choice of the desired equipment. If the participant does not need to constantly visualize in AR - one by one to choose which equipment to use - the process tends to be faster.

The majority of the participants opted for the use of the iPad fixed in conjunction with the external projection. The familiarity with the use of mobile devices influenced the visualization form (iPad fixed or mobile, with or without external projection) during the activities performance. Out of fifteen participants, nine confirmed they were using a tablet for the first time or seldom use a smartphone or tablet, characterizing the low level of familiarity with the mobile devices. Among these, eight chose to position the iPad on a tripod and use the external projection for visualization. Analyzing these data, the conclusion is that this strategy could have been adopted, not only for being considered the best form of visualization, but also for lack of familiarity with the use of this kind of mobile device.

When the participant held the iPad, the AR was visualized in the same position it was before, with the same point of view. On the other hand, when it was used in a fixed position with external projection (situation in which some participants chose in order to have free hands during the task development) the point of view of the external projection was different in relation to the participant’s position, generating
confusion and difficulty in the composition of the leisure area. This way, as mentioned by [17], the visual disorganization can cause ambiguity or difficulty of comprehension for contents in AR. Corroborating with this question, one participant declared: “Just a second, it’s a bit confusing, I am in one place and the iPad in another [...]” - referring to the point of view different from his. This observation matches the study of [18] that compared the visualization by HMD versus the visualization by a computer monitor. These authors concluded that, when the users visualized the AR using the HMD, they had a better performance developing the tasks. In the same way, it was observed in this User Experience evaluation that, when the users moved the iPad, they visualized the AR from the same point of view they were before and that this situation facilitated the understanding of what was being seen.

Among the participants with little familiarity with the use of smartphones and tablets, it was observed more difficulty to handle the markers and organize the urban equipment of leisure areas than the others. The participants who were not accustomed to using mobile devices behaved in a more reserved way, with less agility during the tasks’ performance. Consequently, the familiarity with the mobile devices interfered in the behavior during the task execution. Stressing this observation, if was noticed that all five participants, who indicated that the task of composing a leisure area using AR was difficult, also declared the use of an iPad for the first time or seldom use of smartphones or tablets.

The age, gender and education level of nine participants with little familiarity with mobile devices varied a lot. Among these, four participants declared it was difficult to compose a leisure area using AR. All were female over 41 years old, with education up to a high school level. Therefore, in this User Experience evaluation, the age, gender and education level influenced the difficulty of developing the task. However, it is important to stress that this affirmation is based only on the statements the participants gave at the end of the evaluation in relation to the difficulty of the task execution to compose a leisure area.

From all the participants, only one declared that the way to interact with the urban equipment in AR was not natural; the same participant also affirmed having had difficulty when composing the leisure area using AR. This participant was over 51 years old, female, with education up to junior high and with little familiarity using smartphones or tablets. As there were no more similar cases, it is not possible to draw a conclusion with regard to this question. However, the age group over 41 years old, low education level and little familiarity with the use of mobile devices may have contributed to a greater difficulty interacting with the system.

Among the 15 participants, two declared that the AR system did not have all the desired equipment and other three said nothing about it. This is justified by the fact that only seven different urban equipment of leisure areas were used and did not fulfilled the needs of the participants. During the task performance the participants were encouraged to speak about the experience, express their difficulties and present their ideas - similar to [19]. The desire to use more equipment was evident in the comments registered: “It would be good to use the same equipment twice, I would like to use another multi-purpose court”; “I wanted a swimming pool. A pool is
everything!

8 Conclusion

All the participants were able to recognize multiple leisure equipment simultaneously, even using only the iPad on a tripod, without the option of external projection. The three different layouts tested did not interfere in the result obtained.

Despite the initial difficulty of some, all the participants were able to organize a leisure area with the available equipment. To overcome the initial difficulty, it was necessary to allow all the participants to experiment this technology previously, in order to familiarize themselves with the language of this media.

Differently from the research of [8], in this User Experience evaluation, in general, the participants showed interest in participating, despite their age, familiarity with mobile devices and the AR system. This contributed to the performance of the participants in the tasks.

The majority of the participants chose to use the iPad fixed in conjunction with the external projection. The familiarity with the use of mobile devices influenced the visualization form (iPad fixed or mobile, with or without external projection) during the activities performance. Also, among the participants with little familiarity with the use of smartphones and tablets, it was observed more difficulty to handle the markers and organize the urban equipment of leisure areas than the others.

The result obtained in this evaluation allowed for the development of new directives for the AR technology to be used in PD, that is:

- For the recognition of a set of virtual models (without manipulation), it is recommended the use of an iPad associated with an external projection. This device can stand on a tripod in an angle that allows the visualization of all the set, without occlusions.
- Before the participants have to use the AR system to compose with virtual models, it is necessary that each one of the models to be used be recognized individually. Therefore, it is recommended to perform a section of tuning of recognition before performing the tasks.
- It is necessary to enable a period of use for the participants to familiarize themselves with language of this media. Having the chance of experimenting AR before, the participants can focus on performing the task and not on finding out how to use the system.
- The inclusion of a brief textual description below the image of the marker is indicated to facilitate the choice by the desired equipment.

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References


Understanding face to face interactions in a collaborative setting

Methods and applications

Mani Williams, Jane Burry and Asha Rao

RMIT University

{mani.williams,jane.burry,asha.rao}@rmit.edu.au

Abstract. Extensive studies have shown that face-to-face interactions are a critical component in a work environment. It is an effective communication method that builds trust between team members and creates social ties between colleagues to ease future collaboration. In this paper we present our interaction analysis system that utilized an indoor tracking system to provide insights on the spatial usage and interaction dynamics in collaborative spaces. This gives space layout designers and managers quick feedback on the performance of the space and its occupancies and allows interventions and evaluations to be conducted to fine-tune the space layout or organization structure to achieve optimal performance. We demonstrate our system with data collected from a recent international design workshop.

Keywords: Face-to-face collaboration, indoor tracking, social interaction analysis, team management, workspace design.

1 Introduction

In recent years we have seen a growing interest in monitoring human movement to understand social behaviors for a range of applications from context aware advertising to security and surveillance. This is pushing cutting edge research and development in the field of wireless sensor networks, data mining and visual analytics to develop more effective and efficient ways to track, model and visualize the dynamics of social interactions. For our research we are tapping into this rich multi-disciplinary knowledge to study the dynamics of social interactions that occur in a collaborative teamwork environment.

The pioneer in this field is Alex Pentland who leads the MIT’s Human Dynamics Lab. They have deployed their multimodal wearable sensor system “Sociometric Badges” to study interaction patterns in many large organizations [1]. The Sociometric Badge system extends the traditional laborious data collection techniques in studying collaborative interactions in design processes [2-3] and professional workplaces [4]. Apart from collecting longitude data for studying organizational-wide behaviors, a version of the Sociometric badge system is designed to provide real-time
feedback on the dynamics of a face-to-face interaction, such as a team meeting, to promote better team integration.

Recent findings coming out of the Human Dynamics Lab show that the pattern of social interactions, especially face-to-face interactions, is a very good indicator of the productivity and creativity of a team [1]. Extensive field studies have linked employee productivities with office layout [4]. We see this as a great opportunity for the architecture profession to join and contribute to the discussion of what the future workplace should be.

The center of the Sociometric Badge system is a multimodal data device that records the wearer’s physical movement, voice levels and proximity to others [5]. In many situations this may not be appropriate. Our work focuses on a different approach. Our system is more adaptable in terms of input source and output format. We utilized a commercially available proximity-based indoor tracking system to provide ongoing input data for analysis. The tracking data is processed to produce real-time reports on the face-to-face interaction. The analysis process and resulting visualization is supported by supplementary contextual data from the client. We believe an efficient system is one that is customizable to our client’s needs, which are expected to evolve over time.

We have compiled our research into a deployable system. We have targeted our system for two applications. The real time analysis results allow managers and project teams to monitor the development of projects as they evolve and enable them to respond to changing needs more effectively and efficiently. Our system can also be used to provide reports and feedback on the optimal office layout and the organization structures that operate within it.

In the remainder of this paper we will first introduce the methodology of our system. Next, each stage of our system will be described in detail and be supported by related work. The capability of our system for real world application is demonstrated with a case study. The paper will conclude with a discussion of its two suggested applications and recommendations for implementation in other contexts.
2 Methodology

2.1 Data collection

Adaptation of face-to-face interactions research into industry practice is lagging behind the acceptance of Big Data and virtual communication mining due to the hurdle of deploying a data collection system. Established methods to collect face-to-face interaction data such as questionnaires, surveys or direct observations are resource intensive, subjective and thus hard to integrate into the everyday management decision-making process or design process.

We are interested in tracking human interactions during the subjects’ normal work environment. Tracking data can be in the form of position tracking that records the trajectory of people as they move around, proximity tracking that records the distance between people and/or a person and surroundings [6], or association logging that detects interaction events based on multiple input criteria [5,7]. Lui [8] and Gu [9] surveyed tracking methods and applications. Current wireless sensor networks (WSN) development have achieved indoor positioning accuracy of less than a meter [10].

A suitable data collection system should be automated and non-intrusive. Automation reduces repetitive manual labor and enables a continuous data stream to be available for live analysis and decision-making. We advocate for ethical care to our study participants that ensures participation is voluntary and consensual. A non-intrusive set up, such as a wearable tracking tag that can be removed, allows our participants to have control of their privacy.
When possible, supplementary data should also be collected. These include floor plans, organizational diagram, project description and schedule, as well as automated contextual data such as ambient sound level and other environmental conditions. This information helps us to contextualize and evaluate our analysis.

2.2 Behavior modeling

For us to get meaningful results, we need to build a behavior model that describes the scenarios that we wish to observe. A behavior model needs to be defined and constructed from the collected tracking data, supplemented by the context data. This is one of the opportunities for us to guide the analysis system to be specific on what it is that we are interested in.

Regarding proximity in face-to-face interactions, the classic proxemics theory of Edward T. Hall [11] categorized the four types of interactions (intimate, personal, social-consultive and public) by person-to-person proximity. Waber [12] used spatial constraints such as desk, corridor, floor and building separations to categorize interaction distances. Research in office layout found that both the frequency and the duration of interactions are correlated with employee performance [13]. Frequency and duration can be combined to produce a complex proximity measure [14].

We propose to divide behavior modeling into two components. Firstly filter the input data stream to remove irrelevant data. For example if we wish to study evolution of collaboration dynamics within project teams, we would need to process the data to identify events of collaboration and participants that were involved in those events. Let us suppose that the organization that we are studying supplied us with a list of participants that belonged to a particular project. Through proximity tracking we can identify when the project members met and for how long. If we know the locations of the meetings through position tracking or environmental proximity tracking, or we have access to the project schedules, we can isolate the meetings that were project related.

Once we have a list of individuals and a list of events that link subsets of the individuals together, we can construct an interaction network that represents the behavior model that is specific to our query. We can also introduce dynamics into the network by adding the time variable. With the interaction network at hand we are now set to apply a large array of complex network based analysis and visualization to extract meaning from our behavior model.

2.3 Analysis

Complex Network Analysis (CNA) is a multidisciplinary field of research that investigates relations (network links) between a set of individual identities (network nodes) that are representations of real world phenomena, ranging from human biology to the World Wide Web. Supported by rapid growth in computing power, data collection and storage capacity, CNA is a relatively active area with contributions, both from and to, computer science, mathematics, sociology, biology to name a few.
By constructing our behavior model as a complex network we can apply CNA methods to examine the behavior at multiple levels. We can compare behaviors of individuals by observing their position and importance within the network; group certain individuals together based on contextual attributes and observe interaction within and between the groups; and observe interactions between individuals at the organizational level to get an overview of the underlying structure of the behavior.

Social network centrality measures such as degree, closeness and betweenness [15] are network analysis methods that calculate the importance of a network node within the network. They are calculated based on the number of links a node has (degree), how easily a node can reach the rest of the nodes in the network (closeness) and how critical a node is to the structure of the network (betweenness). Translated to our context an individual with a high degree measure indicates he/she was quite active, since that individual had lots of interactions with a range of people. Looking at the closeness measure allows us to pick out the more integrated individuals; they may not have met with the most people but they tend to have the best idea of how everyone is going, since news (or gossip) travels through fewer paths to reach them. If you want to know the employee you shouldn’t lose, then the betweenness measure would be a good indicator: a person with a high betweenness measure indicates that he or she is the critical node between two sections of the network, if you take him or her out part of the organization may fall apart unless new links are made elsewhere.

In the context of face-to-face interactions in a collaborative work environment we are working with what is called “Small-world networks”, where the people an individual interacts with are mostly likely to also be interacting themselves, or “friends of friends are also friends” [14], [16]. This node level or network level property is called clustering or transitivity [17]. Within a project group an even transitivity means that there was a healthy communication flow between the group members. Another network property of interest is cohesion [18]. Similar to the betweenness centrality measure, cohesion represents how many nodes need to be removed to disconnect the network, it observes how close knit a group is. Studies have shown that at different stages of the creative process different interaction network structure (represented by its cohesiveness) should be encouraged: A star-like diverse network is suitable at the conceptual discovery stage where the project is collecting ideas; a cohesive network is good for the development stage where everyone works together towards the final goal [12]. Both transitivity and cohesion are applicable at a group level as well as the overall organizational level.

Another aspect of group behavior worth investigating, especially in the architectural and design context, is the spatial preference of behaviors. This builds on the proximity analysis component of the behavior modeling stage where we utilized distance dependent proximity readings to generate interaction links. This is best represented graphically, overlaid on a floor plan, to demonstrate the relationship between individual/group/overall activity intensity and space usage.

As behavior is highly dependent on the context, we recommend a more qualitative approach to representing analysis results. Through network visualizations we can compare the change in the behavior pattern across time samples and groups. Supplementary data such as project roles and team assignment can also be included in
the graphical composition of the visualizations to introduce contextual information to assist with result comprehension.

In the remainder of the paper we will demonstrate a combination of the introduced method with a set of real world data collected by the author.

3 Case study

We have collected data from a recent international design workshop attended by students and professionals from the design industry, based on a collaborative teamwork framework where the attendees formed several project teams. The collaborative workshop event aimed to encourage positive interaction within the teams to work towards a common project outcome, stimulate interactions between teams to exchange ideas and skills as well as foster new social, professional and academic connections. Over the course of four days, we have tracked the movement of more than fifty participants using an indoor tracking system.

A set of supplementary data were also collected:
- The development of the project teams was documented through a set of time-lapse cameras.
- Field notes recorded through participant observation by two of the Authors.
- From the workshop organizer we obtained a floor plan with the project activity allocations noted (Fig. 2).
- From the individuals that agreed to participate in the tracking exercise we collected their name and project assignment.
- Publically available information collected were:
  - Workshop schedule, project descriptions, proposed project schedules and names of the project leaders and participants.
Fig. 2. Case study: the floor plan of the workshop. Main activity spaces are marked. Twenty-two tracking beacons (blue dots) were installed near to the activity spaces, where possible, placed in a relatively regular fashion. There were a total of eleven project groups participating in this workshop, out of which tracking data from eight of the project groups were analyzed for this paper.

3.1 Data collection and preparation

The data collection occurred over four days of the workshop event that included: three days of workshop days, one final day of daytime offsite presentation and evening exhibition onsite. During the workshop days the participants had access to the space from approximately 8 am to midnight.

The tracking data collection was conducted using an off-the-shelf ZigBee-based indoor tracking system, which periodically outputs proximities of wearable tags to several static tracking beacons. This allows us to estimate the position of people in a preset space when the tags were carried: the tag position estimates were calculated as the mean X, Y coordinates of the detected beacons’ coordinates, weighted with the corresponding beacon RSSI readings. A log of the position was recorded in a database for further analysis.

Fig. 3. Tracking data showing spatial usage of the eight represented project groups.

3.2 Behavior modeling

We constructed our behavior model based on the tracking tag positions. Data was grouped into 10-minute data samples. Statistical analysis was applied to calculate an activity center and an active area for each of the tags that were present during the data sample. A tag area threshold, determined from experimentation, was applied to
remove idle tags. These tags were most likely to be left on the table or in the person’s
bag thus did not represent the behavior of the person it was assigned to.

Proximity analysis was applied to all of the remaining active tags:

1. Distance was calculated between all of the active tags detected in the
   same data sample. This generated a list of proximities between active tag
   pairs.
2. Referring to the tagged person’s project assignment, we categorized the
   proximity list into in-group proximity and out-group proximity.
3. The out-group proximity threshold of 3-meters was applied to extract a
   list of out-group interaction tag pairs. The 3-meters threshold was
   determined from onsite observation and in consideration of Edward Hall’s
4. As the activity of each of the projects differ, ranging from computer-based
   work to large physical prototype construction, an adaptive in-group
   proximity threshold was required. Through experimentation, we found
   that the mean distance values achieved a good balance between removing
   tag pairs that were too distant to be effectively communicating face-to-
   face and preserving sufficient activity tag links to model in-group
   behavior.

The interaction network was constructed from a subset of the proximity list,
characterized by a time range and/or the participants in the interactions:

- The interaction network node represents the list of active tags present
  during the proximity list. The node attributes were: tagged individual’s
  project allocation and role, the list and count of the activity center
  coordinates that the tag was calculated to have visited and the activity
  centers’ corresponding active area size.
- The interaction network links represent the pairs of activity tag nodes
  from the proximity list. The link attributes were: in-group/out-group
  categorization, the coordinates of the link (taken as the mid-point
  between the connected two tag coordinates).
Fig. 4. Demonstrating the adaptive in-group proximity thresholds (marked). The line plots represent the density distribution of the in-group proximity pair for each of the eight project groups. The color-shaded backgrounds represent all of the out-group proximity pairs that the project group participated in. The gray background represents the distribution of all of the calculated proximity pairs. Looking at the in-group proximity lines, we can see that the RN and DS groups have shape narrow peaks close to the origin, this tells us these groups were physically static. This agrees with the onsite observation: RN and DS were computer-based design projects. Also observe the SG in-group proximity line has two peaks, this indicates the SG group had two modes of operation: our field notes confirms that during this data sample period a select members of the group were tasked to man the project table and others left to visit other projects. Compare the color-shaded out-group proximity with the workshop result in gray, focusing on the region near the group mean threshold, tells us the amount of distraction the group experience and produce. For example for FBR its out-group proximity distribution closely matched with its in-group distribution, translates to that for FBR members within their work radius it is nearly as likely to encounter someone from a different project than one from their own.
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Fig. 5. This is the interaction network that models the behavior of the workshop compiled over the whole data collection period. The network layout was optimized using the force-directed Large Graph Layout algorithm [19-20]. The nodes were colored by their project allocation, and the shape indicates the individuals’ roles: square represented the project leaders and circles represented the participants. As expected the interaction network visualization showed a clustering behavior that coincided with the individuals’ project allocation. The variance between the project groups suggests difference in work patterns, for example the light green (RS), yellow (RN) and orange (SE) project group members appeared to have mingled more with each other.

3.3 Analysis and visualizations

The force-directed network layout (demonstrated in Fig. 5) gives us a good visual overview of the strategic importance each individual contributed to the overall workshop interactions. We can highlight different behaviors by applying the three aforementioned social network centrality measures to the interaction network. Fig. 6 demonstrates the behaviors of individuals in the workshop during an afternoon
session (day 2), using the automated network layout node placement with the node size representing the centrality measure scores.

A cohesive group interaction network represents a healthy collaborative teamwork. This is best represented graphically by constructing an in-group interaction network for each of the project group by extracting the network links that connects the nodes belonging to the same group. A circular node layout was used, as it is best for presenting the interaction patterns. The node shape identifies project roles; node size represents the number of interactions that individual had participated in. A fully cohesive network is one where a balanced network links exist between all of its team members, this is more common in a facilitated meeting; for project work a biased interaction network was expected, as the ones shown in Fig. 7. Our field notes and supplementary data confirmed that during the represented time sample, there were distributions of the tasks to form sub-groups within projects.

In a collaborative co-located work environment, such as the one from the case study workshop, the amount and diversity of out-group activity can be both a blessing and a curse: too much interaction between different groups distracts the team from working on their own projects, but not enough out-group interaction most likely shows that the project has not explored the skillsets and expertise from people outside the project. As seen in Fig. 8, with reference to the floor plan in Fig. 2, project PM was more isolated and had limited interactions with other projects. Interestingly both of the ST (teal) and SG (purple) teams were relatively centrally located but its members did not interact much with other project teams either.

It is worth investigating when a project team was shown to be involved in a large amount of out-group interactions, identify with whom (Fig. 9) and where those interactions occurred (Fig. 10), and if more contextual information is available, check whether the interactions level was a distraction to the teams involved. In the case of the neighboring projects SE and RN the interaction was disruptive and a few screens were requested to construct a barrier between the two project spaces.

Interaction dynamics are difficult to quantify and measure. Presenting the organization-wide analysis result alongside results from individual groups (such as Fig. 8 and Fig. 10) helps the viewer to understand the variation and cause of the interactions. Organization wide dynamics can also be perceived through comparing visualization across time sample. To this end, we divided the data into timed sample blocks: each day’s data was separated into morning (8 am to 1 pm), afternoon (1 pm to 6 pm) and evening (6pm to 8am of the next day), resulting in twelve sample blocks. We then constructed an interaction network for each of the sample blocks and generated the organization interaction diagram based on the degree centrality measure (Fig. 11) and the interaction spatial map (Fig. 12).
Fig. 6. Organization interaction diagrams as recorded during the afternoon session of day 2 of the workshop, using the degree (left), closeness (middle) and betweenness (right) measures represented as node sizes. These respectively corresponded to emphasis on the individuals’ activeness, integration and criticalness, with the node size representing the measure value, and the color indicating the individual’s project allocation.
Fig. 7. In-group behaviors of the eight project groups as recorded during the afternoon session of the day 2 of the workshop. The node shape indicates the individuals’ role: square represented the project leaders and circles represented the participants. From the variations in the weight of the interactions between project group members we can observe sub groups have formed in the projects.

Fig. 8. Ratio between in-group interactions and out-group interactions compared across the eight project groups. Due to its spatial isolation (as seen in Fig. 3), project PM (red) had limited interactions with other projects. Interestingly the SG and ST teams were relatively centrally located but its members did not interact much with other project teams.
Out-group behaviors of each of the project groups, the interaction participants are highlighted in the organization interaction diagram. Interesting observation comparing SG and FBR projects: although SG team had conducted more in-group interactions during this workshop session, it has met up with a large proportion of the workshop participants; whereas FBR group member’s out-group interactions were more frequent but more selective.

Interaction spatial maps, top: Locations of where the project groups engaged in in-group interactions (colored) and out-group interactions (gray); bottom: The group data is combined to produce the spatial interaction map for the organization.
Fig. 11. The organizational-wide interaction diagrams, individual level interaction intensity are emphasized by the size of the individual nodes (degree centrality). Day 1 to 3 were workshop days, day 4 was the final day consisting of a daytime offsite presentation and evening onsite exhibition. Node color represents project associations. As we can see from the twelve sequential diagrams, as expected, the interactions that occurred showed high project clustering preference, but of more interest to us is that through these diagrams we can also observe variations between the sample time periods: The interactions became more project orientated as time progressed towards the conclusions of the workshop (on day 3), this is vastly different from the interactions that occurred during the exhibition (evening of day 4) when people mingled while visiting each other’s project exhibit.
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Fig. 12. The organization-wide spatial interaction maps showing the locations of in-group interactions (colored pink) and out-group interactions (black), as recorded by the four days of tracking data. Presented spatially and sequentially we can clearly observe the change in the spatial usage of the workshop as the workshop progressed. The increase in in-group interaction intensity observed from the interaction diagram shown in Fig. 11 can also be seen here: The color intensity in the day 3 diagrams is more evenly distributed compared with day 1 and 2.

3.4 Interpretation

As mentioned above, goals of the outcome of the workshop are to provide an environment for attendees to participant in one of the allocated projects, as well as to stimulate idea exchange and foster new personal connections between the attendees. For many people this was a constant balancing act, “I really wanted to see the other projects, but I needed to get this done first.” Project PM (colored red) had requested an isolated space to provide a stable test environment for its experiments. From Fig. 11 we could see the impact of this spatial segmentation had on the workshop-wide interaction network: the PM members had formed a close-knit cluster with little interactions with others. Some relief from this isolation can be seen on the afternoons of day 1 and day 2, when the workshop had organized presentations attended by everyone, although it is clear that this temporal integration had little long-term impact. From this we can conclude that spatial segmentation should be avoided in future workshops, in cases where a controlled environment is required, temporal partition is preferable to permanent separation of project spaces.
Too much spatial overlap can also introduce issues. Project SE (orange) was assigned two spaces, one in the building atrium, one in the bottom left end of the long open studio space. This meant there was regular traffic between these two spaces, directly impacting the operation of the RN (yellow) group. Before long, two movable screens were put in place to provide partition between RN’s space and SE’s space. In this case, the Fig. 10 spatial heat maps clearly demonstrate the disadvantaged situation of the RN project: they have the smallest in-group heat map because their in-group interaction was over flooded by the distractions from their neighbors. This could also be seen from the Fig. 4 proximity distribution. The RN group had the narrower in-group proximity plot; this indicates that the RN had positioned themselves physically close to each other, most likely to stay away from the foot traffic. In comparison, project FBR (purple) was also centrally located with possible distractions coming from three sides, but as seen in Fig. 10, they managed more undistracted in-group interactions. This was because the FBR was allocated a wide space, which acted as buffer to protect the project from unintentional distractions. Based on these observations and interpretations, we recommend that future workshop space allocation consider traffic distractions around projects and allocate additional buffer spaces to projects that may be affected.

Looking across the time samples (Fig. 11 and Fig. 12), we could detect the increase in the preference of in-group interactions throughout the workshop as the projects progressed closer to completion (end of day 3). The organization-wide interaction diagram (Fig. 11) became more clustered according to project colors, and the spatial map (Fig. 12) became more saturated with in-group interactions. This is an accurate indication of the status of the healthy project progress.

4 Applications

We have presented a proximity-based interaction analysis system to give us insights into many aspects of the collaborative environment. In this section, we will demonstrate how our methods can be used for other real world applications.

4.1 Office Spaces

Office spaces have shifted from individual cell based configuration towards a flexible open-plan with mixed-use zoning configuration. Driven by commercial incentives [4], and supported by research suggesting that an increase in informal interactions between employees have positive contribution to productivity [1], [12-13], this trend is sure to continue.

Although the literature still debates the quantity and quality of interaction that achieves best workplace performance, extensive research supports the proposition that the geometrical layout influences human behavior and communication patterns between individuals [13].

Existing organization-planning studies are still heavily dependent on a questionnaire approach to collect interaction data. Questionnaires are known to be
subjective and have a low response rate. In comparison, our wearable sensors data collector is non-intrusive and is capable of providing automatic and objective interactive data. Our analysis system can then generate live reports on the current interaction patterns in the workplace. For optimal organization performance, interaction patterns should match the organization structure and task dependencies. Our reports (Fig. 7-11) allow organizers to identify and encourage positive interactions as well as implement early intervention to remove distractions.

Ongoing spatial usage evaluation is required to ensure the compatibility between the spatial layout and the intended interactions. Current space auditing processes are still manual observation based, require timed visits by observers to each of the designated spaces to conduct head counts. Our interaction analysis system can automatically produce historic reports of the space usage (Fig. 10 and Fig. 12). This information is valuable for the active management of workplaces [4]. For example, the outcomes from the interaction analysis can be used to flag spaces that require activation and recommend reconfiguration of employee desk allocation.

4.2 Project Management

A project team can use the in-group interaction diagram (Fig. 7) to manage the communications in the team. The team members can become more aware of the dynamic of the in-group interactions through monitoring the real-time report of the in-group interactions. This should encourage a more balanced contribution of the team members, build trust and integration within the team and contribute to better overall performance. The out-group interaction diagram (Fig. 9) is useful to identify expertise from the organization to be included in the project.

On a higher level, company management can also gain insights from interaction analysis. From the individual level analysis such as degree and betweenness centrality measures (Fig. 6) we can discover persons and relationships that may require additional support or to be encouraged through reward. A combination of face-to-face in-group engagement and out-group exploration is indicative of the creativity and productive level of a project team [1]. Although the context of each project can be unique, the availability of live and historic interaction data allows the managers to have close engagement with the teams to find the winning formula for best performance.

4.3 Remark

It is important to refer to other contextual information before making any judgment on the performance of the individual or a group. Each scenario is unique, and how people interact also changes with time. When possible, multiple data sources should be tracked and fed into the behavior model. The face-to-face interaction analysis methods presented in this paper can be easily adapted to be applied to other interaction data sources, such as email communications, social media engagement and other virtual interactions. Those data sources can be combined with tracking data
through additional proximity analysis methods, such as multi-criteria threshold, or be processed independently and combined with tracking data results at the visualization stage through the use of graphical annotations or overlays.

5 Conclusion

In this paper we present our development of a face-to-face interaction analysis system that is targeted for use in collaborative work environments to generate insights on how people interact with each other.

We have demonstrated the capability of our system using the data recorded at a recent international design workshop. By focusing on visual presentations our analysis methods were able to uncover insightful engagement patterns that informed us of a range of dynamic behaviors including participant engagements, project group collaboration and overall workshop dynamic. In specific to this case study, our analysis was able to identify scenarios of interest and provide recommendations for the planning of future events.

The system and methods presented here have applications in increasing the program compatibility of office layout designs, supporting an active workspace management for efficient facility usage, as well as improving team performance at both an individual and a management level.

Our research contributes to the advancement in the field of architecture and computation by connecting our profession with the cutting-edge development in social mining and people analytics, thus preparing us to actively engage with the changing social context that is surely to come with “the next city”.

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References


Intelligent architectural settings using a computer vision based visual analytic interface

Eric Sauda, Chris Beorkrem, Richard Souvenir, Donna Lanclos and Scott Spurlock

University of North Carolina at Charlotte
{ejsauda, CBeorkrem, souvenir, dlanclos, sspurloc}@uncc.edu

Abstract. This paper presents a framework to enable the understanding and designing of interactive architectural settings. We present our work in interactive public displays in the lobbies of university buildings, demonstrating both the design and evaluative dimensions. We identify the need for a method to understand meaningful behavior in architectural settings. We then present a unique approach combining computer vision and ethnography in a visual analytic interface using the SENSING Toolkit, a computer vision framework for collecting and storing long-term, large-scale human motion, and VALSE (Visual Analytics for Large-Scale Ethnography) an interactive, visual analytic interface called designed to allow domain experts to query and understand the data. Finally, we propose a new concept of media rich spaces that we call intelligent architectural settings.

Keywords: Smart buildings, computer vision, ethnography, visual analytics.

1 Introduction

How can the new forms of computational interaction and surveillance be understood in the context of architectural design? How might such tools be evaluated relative to the intentions of the designer? How might interactive spaces be responsive to the changing and particular needs of its users?

Within architectural practice, answers to these questions have remained either anecdotal or fragmentary. Within architecture practice, the idea of a new role for digital media (cameras and monitors) as part of the space of building often included as part of the programming of a building, but little thought has been given to the way in which this may transform our understanding of the architectural setting. For example, in the case of (removed for blind review). at our university, a media wall is included in the building without any programming of either the hardware or the interaction. In other cases, architects have designed installations using interactive media, but usually with very specific and restricted form of interaction.

The (removed for blind review). research group includes faculty from architecture, computer vision, and anthropology. As part of our on-going work, we have developed methods for the analysis of media rich environments. During the course of this research, we realized the need for a more fulsome and meaningful understanding of...
architectural settings, and we understood the possible role that applied ethnography and computer vision could play. This method can capture meaningful behavior in architectural settings over long time frames, and would afford designers the opportunity to study the programmatic and human-centric performance of such settings with higher levels of accuracy and assurance. It also holds the promise of unique insights for architectural design and performance.

The goal of our work is to use the VALSE (Visual Analytics for Large-Scale Ethnography) system to create intelligent architectural settings, which in contrast to existing interactive systems are programmable, adaptable and focused on meaningful behavior.

2 Evaluation of Interactive Architectural Settings

We have conducted research and design of interactive public displays over the last five years. Our most recent test bed for this work was the lobby of a new campus building, located in (removed for blind review). This building serves primarily as a combination of both office space and educational classrooms, and the lobby is a 4,000 sq. ft. space that serves as the primary circulation route from the main entrance to the elevators. The space is adjacent to a coffee shop and serves a variety of purposes including, a lounge space and venue for hosting art exhibits and corporate events.

![Lobby of the (removed for blind review) (as viewed from one of nine ceiling-mounted cameras).](image)

Our beginning studies of nearly 100 installations and public information displays from fields including architecture, art and computer science led us to conclude that there was the need for a systematic method of design and evaluation. We developed such a system that included space, hardware, processing and behavior as the four critical components.

Space was described using standard orthographic representations of plan and
section. Since these are the best understood within the architectural community, we began with these as a standard description onto which we would map the other analysis. Our objective was to work toward a more useful and fulsome vocabulary for the description of interactive spaces that would supplement the normative representations.

Hardware analysis included a surprisingly wide variety of components, ranging from data projectors to flat panel displays to microphones to speakers to cameras to motion sensors. We quickly determined that it was important to understand the spatial implication of each component; for example, data projectors and LED displays both can be used for image display, but critical differences emerged from the case studies that include size of the image, sensitivity to ambient light, ability to project on floors and ceilings and sensitivity to occlusion. We developed a set of graphic icons that captured the spatial extensions of each hardware device. We were then able to map these symbols onto the floor plans and sections in a way that spatialized their effects.

![Diagram of proxemic relations and hardware](image)

**Fig. 2** Representational diagrams of the proxemic relations of individuals and groups to the Digital Tunnel and Digital Tunnel flow chart. Upper left is a pair of sections with devices indicated. Upper right is the menu of hardware symbols. Below is a diagram of the processing logic of one installation. Note the inclusion of device symbol with the flow chart of the processing.

Processing covered all variable connections between the hardware, the space and behavior, typically controlled by digital devices of varying complexity and programmability. To capture the central flow of decision-making we used flow charts, a graphic device often used in computer science. We placed each hardware device
within the box of a flow chart, cross-referencing the spatial description with the flow of information. In almost all of the installations that we studied, the processing was relatively simple, often including only rudimentary motion triggers and image capture and projection.

Behavior proved to be the most difficult aspect of the design to capture. We began with an idea of “ant trails”, showing the path of each user individually of the aggregate. These quickly proved to be very difficult to display as multiple paths overlapped and obscured a clear reading. We added “heat maps” of a regular floor grid. This allowed us quickly compare the patterns of occupation generated by different installations for individual occupation and aggregated behavior over much longer periods of time.

Fig. 3: Mapping of behavior in an installation. Note “ant trails” and heat maps, as well as the qualitative evaluation based on observation and activity/gesture collection.
The objective information generated by this approach did not allow us to understand a large part of the reactions to the installations. Therefore, we decided to include a narrative of the experience of the user. We included general observations of the behavior of users as well as specific activities and gestures. While this method allowed us to record aspects that would be otherwise impossible to capture (surprise, delight, fear, anxiety), it did not provide us much help with the variability of the experience of any installation.

![Fig. 4: Interactive installations in the lobby of (removed for blind review).](image)

Based on our study of existing installations and armed with this method for analysis, we did a series of 20 installations in the available locations. We used a combination of an array of large scale display screens, a forward facing camera, a rear mounted computer running Quartz composer or Processing to capture image sequences and provide interaction. Each of these installations was in place for at least two weeks, allowing us to study the operation of the systems and the reactions by users.

These interactive experiments identified some anticipated behavior (approaching the screen, making noise, degree of motion, etc.) and a possible response by the installation (alteration of the mirrored images, generation of diagrams of movement on the screen, etc.).

It became clear that the capture of behavior was a critical shortcoming in both our experimental work and in the field of interactive displays. The subtlety and variety of behavior we observed in the space was reduced to one or two preset responses. We needed a way to understand and use meaningful behavior in these settings, and to integrate them into the designs. In collaboration with our colleagues in the (removed for blind review), we began to develop a computer vision based method for the
collection and analysis of ethnographic data.

3 Applied Ethnography

A member of our team, (removed for blind review) staff anthropologist at the University Library at (removed for blind review), had led our ethnographic studies of the public interaction in university buildings.

The anthropological understanding of space has moved from the colonial notion that a physical location shapes culture and to the notion that there is instead a sense of place, created by certain spaces. Place is constructed from a complex interaction of everyday practices [1], memories, and imagination, and is overlain on and related to physical spaces, but also distinct from them [2-4]. Particularly prominent in anthropological studies are concerns about social structures that infuse and create public spaces. These social structures inform the ways that people encounter not only physical spaces, but also the people they find and interact with within those places [5-7]. Despite this focus, anthropologists have struggled to address the fact that human behavior is not only taking place in physical spaces, but virtual ones as well, where observation requires going beyond traditional social science field methods.

Place, then, is produced by the dwelling of people in space. Place is an artifact, a processual entity generated by the occupation, interpretation, imagination, and memory of people associated with/living within the space. The interaction of people with space gives meaning to place. Sense of place cannot exist in the absence of people; for example, home is a specific kind of place. The meanings people associate with place rise from individual interactions that are situated in larger cultural structures and identities.

Contemporary discussions within anthropology are also informed by the experiences of people who are immigrants, or otherwise displaced. Their attachment to and creation of place is often accompanied by a dislocation, or an inability to feel at home in places where they are forced to try to live their lives. In these cases, notions of place become even more separated from physical spaces, to the extent that some places only exist in the minds and memories of people, no longer to be found in the physical world at all.

Particularly prominent in anthropological eyes are concerns about the social structures that infuse and create public spaces, and so inform the ways that people encounter not just the physical spaces that underlie the place, but also the people they find and interact with within those places.

Ethnography provides an analytical method of seeing culturally and socially situated practices [8, 9]. Architectural settings become places by virtue of the interactions that take place in them, and the meanings inscribed upon those spaces in the course of those interactions. Thus, a critical step in our research process is to get at the meaning of those places and interactions.
Fig. 5. Example of typical collection of ethnographic data in library setting, using direct observation and hand annotated plans. Study includes position, motion and activity data, collected at 20 minute intervals over a four hour period.

As a background to developing the VALSE tool, we used our research in interactive environments and conducted regular observations within a university library [10, 11], thus providing qualitative descriptive data of the contexts and content of the interactions. Researchers devised structured interview questions arising from the observation data, and the cycle of interviews and observations continued throughout the project. The interview texts as well as the observation notes were analyzed and coded by the anthropologist and a graduate assistant, and the data helped inform the design of the VALSE toolkit and its adaptations, serve as ground truth to test the toolkit, and deeply analyze the impact of the technology in the spaces. In turn, we expect the deployment of the toolkit to enable researchers to examine meaningful behavior at a scale not possible without automated tools.
Fig. 6. Example of typical collection of ethnographic data in library setting, using direct observation and hand annotated plans. Study includes position, time and use of both digital (computer, laptop, tablet, phone) and analog (books, paper, pencil) devices. Data was collected over a 24 hour period.
4 Computer Vision

We began our studies with interactive architectural settings, by extending our observational methods to include a computer vision system to supplement the ethnographic studies. This allowed us to expand our interests to include an investigation of interactive computing in public spaces, supplemented by a system capable of analyzing the ways in which users reacted and used the environment surrounding the interactive place.[27-36].

Fig. 7. Diagram showing the camera view cones for the computer vision array. By overlapping nine different cameras within the (removed for blind review), we are able to compensate for occlusion by objects and other people within a space.

After our installation, the entire lobby space can be observed from a network of nine ceiling-mounted cameras. Preliminary versions of the applications have been deployed to the displays and computers, and initial versions of the computer vision algorithms described have been implemented on the camera network. In the lobby, interactive applications were re-deployed to an eight-panel LED display with co-located microphones and speakers. We conducted small-scale ethnographic observations to confirm the content and meaning of human interaction within the lobby space. The users included students, faculty, and visitors, and the areas around these displays are open and unrestricted, affording opportunities to engage large audiences. In addition, as part of this effort, we analyzed the intersection of technology, space and behavior, continuing to produce a series of analytic diagrams both for existing installations and for our test in this space.

Two members of our team, (removed for blind review) of the (removed for blind review) have developed tools that enable our research group to capture and interpret
ethnographic data in architectural spaces. Traditionally, video has been used in scientific research primarily for manual data collection and analysis [12, 13]. In the social sciences, automated methods for video analysis are not widely used [14].

Recent advances in computer vision have brought automated analysis of human motion within reach. We have developed the SENSING Toolkit, a framework for collecting and storing long-term, large-scale human motion. Our framework is designed to use a computer vision system, including a network of cameras installed in large indoor spaces, such as building lobbies. The system uses ray-tracing logic to triangulate locations, track movement and collect metrically accurate locations of where people have been over time, as well as identify activities that were undertaken while they occupied a location. All of this data is collected while protecting the anonymity of the user, by never recording their actual image.

Data collection is just the start, however. To facilitate analysis over very long timeframes, we have developed an interactive, visual analysis interface called VALSE (Visual Analytics for Large-Scale Ethnography), designed to allow domain experts to query and understand the data. VALSE follows a many-coordinated-views paradigm to present a user with motion summaries such as heat maps, scatter plots, and motion trails, as well as avatar-based, animated reconstructions of activity. These visualizations can be dynamically customized with user-defined time intervals for targeted analysis, and replayed using a familiar DVR-style interface. This type of tool can expand the reach of traditional social science analysis. VALSE leverages the ability of human ethnographers to recognize meaningful patterns of behavior with the computational ability to apply these insights for very extended periods of time.

![Diagram of the system architecture. The SENSING Toolkit will provide an API for applications to analyze and respond to activity in large spaces. VALSE is built upon the SENSING Toolkit provides tools for visualizing and annotating motions.](image)

Large-scale analysis of human behavior in architectural settings requires an understanding of more complex activities than simple gestures. For example, the sequence of a person waving then walking towards another person, then stopping may correspond to the behavior meeting a familiar person. Methods for detecting atomic human actions (e.g., walking, waving) from video have become increasingly accurate; however, there has been less success at recognizing activities (e.g., meeting, dancing, studying).

Ontologies [18, 19], which are widely used in AI, knowledge engineering, and informatics, provide a representation of the concepts and relationships of a particular domain. In computer vision, ontologies have been used to understand hierarchical semantic relationships. However, since our ultimate goal is to develop tools for
analysis and practical inquiry/design, this type of top-down categorization could limit the possibilities of data exploration.

We are implementing a data-driven approach for learning behaviors from gestures. Domain-specific data (e.g., people moving through a lobby) contains common, repeated, related motion patterns. We use the base gestures to learn higher-level behaviors using data stream mining methods. We extend the Episode Discovery algorithm\[26] for finding overrepresented gesture sequences in large data collections and discover clusters of interactions that are closely related in time and apply significance testing on discovered clusters to generate sets of significant episodes based on the frequency of occurrence, length, and regularity. This data-driven approach is used to learn new behaviors that will likely correspond to a single semantic concept. We develop higher-order models by encoding the discovered sequences of gestures and continuing to build a hierarchy of behavior patterns. In addition to validation of automatically discovered behaviors, we allow investigators to use the visual analytics tools to identify motion behaviors of interest. By selecting an example of a motion or activity pattern from video, its constituent gestures can be used as the definition of a new motion motif. Collectively, these tools support the aim of having a user, untrained in computer vision, define and query for problem-specific motifs of complex behavior.

Our public lobby display test bed allowed us to test all the elements necessary for constructing an intelligent architectural setting and to coordinate their operation, but there also were significant problems with this setting. The range of behaviors contained within this space was heterogeneous and ill defined, and has made the ethnographic study of behavior difficult. The requirement that the display be the sole venue for response also limited the range of implementation strategies for the system. Based on these insights, we believe that more focused architectural settings would be more effective for future studies.

5 Toward an Intelligent Architectural Setting

The work of our group combining computer vision and ethnography into the VALSE system offers us the opportunity to understand behavior in architectural settings in a meaningful way over long time frames, including the possibility of real time understanding and response. The combination of human insight from ethnographers and the computational extension from computer vision is a powerful example of a human-computer analytic system.

How might this new ability change the way in which architectural settings are designed and analyzed?

In our work, we draw the distinction between “interactive” architectural settings and “intelligent” architectural systems. Interactive systems have a preset logic of response to the behavior of users, often limited by the capabilities of the display hardware and software. Intelligent systems have the ability to identify and understand meaningful behavior and can be programmed to respond with a wide variety of responses.

An intelligent architectural setting would allow us to understand space in several new ways;

First, we have the ability to get “hard” data on how human behavior is affected by
the design strategy employed in a particular space. Designers have often used spatial and programmatic organizational strategies to justify experimentations in architectural form. For the first time we would be able to monitor the results of these experiments and evaluate their results. This offers us the possibility to create a broad analysis of design intentions; imagine a school design that can actually be analyzed for its ability to encourage positive and engaging behavior from its students and teachers, and that can be generalized over hundreds of design examples. Particularly those architectural sub-fields that build multiple instances of a common design would be able to learn from each new design and improve subsequent instances. We can also monitor how changes to a facility, for example a hospital waiting room, affect the behaviors of the occupants. If a hospital were to reorganize the furniture in their waiting room, does that have an impact on the way in which users occupy the space? Do the users change the space on their own? How might we use this knowledge to make more useful and comfortable settings?

Second, there is the possibility of the development of real time responsive environments, able to interpret behavior and suggest short term or immediately adaptive settings. Imagine an Alzheimer facility that is not just bricks and mortar but is able to track and understand the meaningful behaviors of the patients 24 hours a day, 365 days a year, understanding individual variation in behavior over both the short and the long term. For example, Alzheimer patients typically have trouble with spatial and visual issues, unable to distinguish between a shadow cast on the floor and a step. Intelligent architectural settings will be able to maintain surveillance and understand the changes in meaningful behavior. This could be a flexible and programmable architectural setting that could become a part of the therapeutic setting, allowing adjustments to individual patient’s therapy, creating an improved quality of life for the residents.

6 Future Work

The characteristics for potential investigations include facilities and institutions that are often designed based on previous iterations and organizational strategies. Certain building typologies fall into this category specifically, housing, hospitals and health care clinics and schools. As design has adapted to the information age, it has identified these programs as having an architectural and organizational character based upon learned observation. For example, hospitals and clinics have identified efficient floor plate strategies, which create better working environments for their employees and more effective healing spaces for their users. Based on previous examples, firms will make subtle changes to these layouts to attempt to improve upon previous strategies but they often are reusing proven strategies.

Given these primary evaluation criteria we have been working with several national firms specializing in health care and education who are potential partners for future work. We have identified several immediate targets with these firms. Areas such a waiting rooms are usually ill-defined spaces, without any accurate way to assess their operation. Gathering data over long periods of time with ethnographic insight will allow the design to understand how these areas are used and how they might respond. It might also lead to the incorporation of physical and ubiquitous computing into these settings.
VALSE provides for an anonymous strategy for monitoring users without compromising their identities. This would allow us to capture valuable information about the operation of the facility, identifying areas of operational concern and enhancing positive behaviors. We envision scenarios where RFID tags could be linked to the VALSE data to allow for a more articulated understanding of the movements and activities of team members. This would allow for the general public to move anonymously through the system while employees are identified to provide more fulsome understanding of their movement and activities.

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Intelligent architectural settings using a computer vision based visual analytic interface


Accuracy and ambiguity

Geometric reconstruction of a seventh century stone temple in Hanchey, Cambodia

Sambit Datta

Curtin University
Sambit.Datta@curtin.edu.au

Abstract. Modeling the fragmented and heavily eroded remains of early temple architecture poses several challenges in accurate reconstruction of shape and form from digitally acquired datasets. This paper describes a collection of stepwise ad-hoc modeling methods that can re-assemble ambiguous and fragmentary evidence to provide a robust and empirical platform for the reconstruction of ruined temples. The paper presents the results of the method and the degree of accuracy and ambiguity in the acquisition, processing and reconstruction phases. A key aspect of the method is the maintenance of multiple “ground truths” from plural sources of partial evidence. Key findings of the paper demonstrate early results from the manipulation of geometric modeling primitives based on point collections, an advance in extending the classical tools of architectural analysis and comparison. The problem of accuracy and ambiguity in these methods and their algorithmic implementation is the subject of further investigation.

Keywords: Digital data acquisition, flexible modeling, heritage reconstruction and visualization

1 Introduction

Digital reconstruction is a well-established methodology in the study of historical structures. Reconstructions have a wide number of applications in the scholarly study of past architecture, formulation of theoretical positions, conservation and physical restoration of monuments as well as virtual simulations for mass consumption in galleries and museums (Malpas, 2008). One area of work that has received relatively less attention is the virtual re-assembly of historic structures from deformed datasets. In particular, the assumptions of accuracy and ambiguity in recovering robust information from acquired datasets remain a significant problem (Affleck et al, 2005). This paper presents a digital workflow for modelling deformations in historic buildings. The elements of the workflow are illustrated through the analysis of a digital reconstruction of the structural geometry of a seventh century stone temple in Hanchey, Cambodia (Figure 1). Each step in the workflow and the problems associated with historical accuracy and the handling of ambiguity is described. The
aim of the paper is to identify these issues, particularly in the cases of temple architecture (heavily eroded surfaces, structural deformation and missing parts) encountered in South and Southeast Asia.

Fig. 1. The Kuk Preah Theit Temple in Hanchey, Cambodia (left). The geometry of the temple is reconstructed by recovering schematic geometries from sparse structure-from-motion datasets (centre). (source: Adapted from Datta and Beynon, 2014)

A crucial difficulty faced in digital reconstruction is the recovery of structural and architectonic details from digital datasets. This is further compounded in historic buildings, where missing information, fragmented and heavily eroded and loss of structural and formal integrity through the ravages of time render the process of establishing formal continuity between artifact and reconstruction difficult. In this context, computational techniques that can re-assemble fragmentary evidence, provide robust and empirical methods to fill in missing information and generate and test the accuracy and ambiguities in the digital reconstruction of geometry are necessary. This paper examines how digital modeling methods and workflows can extend the classical tools of model reconstruction from surface geometry of architectural scenes to structural information to the construction of solid parts-based models. The paper focuses on the need to mediate between accuracy and ambiguity in the interpretation of data provided by computational acquisition tools such as image-based techniques and point cloud sampling methods. In doing so, it relies on the conventional methods of architectural abstraction and analysis to provide guidance in the process of reconstruction through a series of stepwise incremental reconstructions.

2 Related Work

Computational means of acquisition such as photogrammetry, combined with parametric modelling and simulation become useful methods for projective reconstruction from multiple sources of partial evidence. Therefore, a wide range of methods, datasets, workflows and outputs has been proposed to fit these applications (Debevec et al, 1996; Streilen et al 1998). Datta and Beynon (2005) demonstrate the application of a hybrid computational approach to the problem of recovering the
surface geometry of early temple superstructures. The approach combines field measurements of temples with close-range architectural photogrammetry. The datasets are processed with rule-based generation and parametric modeling techniques. The extraction of higher order features from point sets is demonstrated in computational modeling (Daniels et al, 2008) with applications in recovery of complex curves from traditional buildings. The use of sophisticated techniques for the acquisition of historic sites has been developed for uncovering archeological landscapes (Evans et al, 2013).

The architecture of the temples of Southeast Asia owe their compositional characteristics to adherence to canonical treatises, the interpretation of priest-architects or the usage of earlier examples as architectural models for later ones (Smith, 1999; Dumarçay, 2004; Haendel et al, 2012). The fragmented discontinuity of textual accounts, lack of graphical representations and heavily eroded early remains render the process of establishing the lineage of formal continuity between canon and construction difficult. It has been speculated whether the architecture of these temples owe their compositional characteristics to adherence to treatises, the interpretation of priest-architects or the usage of earlier examples as architectural models for later ones (Meister, 1979; Indorf, 2006).

3 Overview

Fig. 2. Kuk Preah Theit Temple, Hanchey, Cambodia. The present temple is physically reconstructed. (source: Adapted from Datta and Beynon, 2014)

This paper extends previous findings on the reconstruction processes suitable for explaining historical building traditions in South and Southeast Asia. It forms part of a larger project on understanding the compositional and architectural linkages between the temple building traditions of South and Southeast Asia (Datta and Beynon, 2014). By focusing digital methods on analysis of plans, layout and proportion of wall ensembles, superstructure form and constructional and ornamental motifs, our work shows how the earliest Southeast Asian temples represent lineages that were constantly being adapted and refined from their genesis of the archetypal Brahmanic/Hindu temple.
The early temple architecture of Southeast Asia, presents a remarkable and intriguing body of evidence in support of inter-Asian connections. Seen as a collective corpus, these sites establish a consistent pattern of religious, cultural and technological ideas that transcend national or geographic boundaries (Chihara, 1996; Chapman, 2012).

In the absence of local textual records, the evidence embedded in the geometric and material composition of the surviving monuments is the main, and sometimes the only evidence by which a more conclusive understanding of the relation between theory and practice in these buildings might be developed (Meister, 1985; Datta, 2007). The motivations for the reconstruction and recovery of the three dimensional forms are to develop a digital dataset of early Indian antecedents, test new technologies for the acquisition of built heritage and develop new methods for comparative analysis of built form geometry.

4 The temple of Kuk Preah Thiet, Hanchey, Cambodia

4.1 Historical Background

The temple of Kuk Preah Thiet is located in Hanchey (Han Chei) about twenty kilometres north of Kompong Cham, occupying a prominent hilltop on the west bank of the Mekong river. While presently dominated by a modern wat, Hanchey is significant as the location of three pre-Angkor shrines, each in a distinctly different idiom, as well as the remains of several other buildings that have yet to be fully investigated (Datta and Beynon, 2014). There is a brick temple (original name unknown, now referred to as Hanchey A), a small cubic stone-slab cella known as Hanchey B (Indorf 2006), and the most unusual stone temple of Kuk Preah Thiet. Two inscriptions on the inner door pillars of Hanchey A were among the first discovered and were long considered as the most ancient in Cambodia. (Figure 2).

Historically, Hanchey seems to have been an area where different Khmer polities converged in the fifth to eighth centuries, though never a major centre of power itself. Down the hill and closer to the banks of the Mekong is the temple of Kuk Preah Thiet. Attributed to the ruler Bhavavarman (though dateable to well after his death) these inscriptions indicate that the site, if not the temples themselves, dates back to the second half of the sixth century. The pre-angkorian shrine of Kuk Preah Thiet, therefore represents one of the earliest known stone temples in Southeast Asia. It is lithic in its conception, constructed of dressed stone (Figure 5) and has a storeyed pyramidal superstructure composed of tiers. The elements of this shrine can be traced to many antecedents in the Gupta period. However, the early date of the temple, its well developed superstructure and its proximity to known Gupta examples, makes it a crucial example of the pre-Angkorian temple corpus. Parmentier’s 1927 photograph of the temple ensemble (left), measured drawing of the plan of Kuk Preah Thiet Temple, Hanchey, Cambodia (centre) and conjectural drawing of the east facade (source: Parmentier, 1927:200) (Figure 3).
The cuboidal cella sits on a solid *jagati* (platform) with a distinctive *vedibandha* molding which is partially buried and yet to be excavated. The *jangha* or wall portion of the sanctuary is largely bare and simple. The distinctive *candrasala* motif appears on the superstructure tiers. The *Vamana* temple at *Marhia* and the *Siva* temple at *Bhumara* have similar bases, treatment of wall and motifs (Chandra, 1970). However, the most significant aspect of this sanctuary is the *Phamsana* (tiered pyramidal) superstructure with a distinctive molding. In contrast to flat roofed temples, and the more developed superstructures at Sambor Prei Kuk and at Phnom Kulen, this temple has the tiered pyramidal form of superstructure, known from earlier wooden temples adopted in stone. The significance of the temple lies the early date of the architectural composition of its superstructure, a pyramidal composition in three tiers, known as Phamsana in the literature, predating the development of the majestic temple complexes of the Angkorian period (Datta and Beynon, 2014).

A cubic temple with a pyramidal roof, Kuk Preah Thiet is constructed of dressed basalt blocks. It has been partially stabilised and currently remains at risk of structural collapse. Kuk Preah Thiet is in its present state reconstructed, though at the time of the authors’ visit, so inadequately founded that the building is at risk of collapse. The ruinous state of the temple, in an advanced state of collapse, makes dimensional correlation very difficult. Structural deformation, missing elements, surface erosion of the soft volcanic basalt stone, contribute to the difficulties in establishing accurate measures.

To investigate the inherent ambiguity in establishing accurate measures, the virtual reconstructions, in particular the recovery of schematic profile information, can play a key role in establishing the architectural ideas underlying the temple. Secondly, the reconstructions can be used to establish its relationship to earlier Indic, Javanese and Khmer temples as well as dimensional correlation with prescriptions in surviving temple construction manuals.

![Fig. 3. Parmentier’s 1927 photograph of the temple ensemble (left), measured drawing of the plan of Kuk Preah Thiet Temple, Hanchey, Cambodia (centre) and conjectural drawing of the east facade (source: Parmentier, 1927:200)](image)
5 Geometric Reconstruction Workflow

The Kuk Preah Thiet temple at Hanchey is heavily eroded, virtual reconstruction models play a key aspect in establishing the the architectonic ideas underlying the earliest Indic, Javanese and Khmer temples and their relationships to canonical texts. To determine these connections, two and three-dimensional geometric dissections from the temple are analyzed and compared to measure and reconstruct their geometric properties. Fragments of evidence are brought together from field measurements, relating these to mathematical and geometric descriptions in canonical texts and proposing “best-fit” models. To recover the constructive principles underlying this temple, field measurements and close-range photogrammetry were combined with rule-based abstraction, and parameterized models.

The digital reconstruction process requires bringing together fragments of evidence from field measurements, relating these to mathematical and geometric descriptions in canonical geometry and proposing “best-fit” models (Figure 4). These digital methodologies permit the creation of the following types of 3D reconstruction models:

- Raw surface reconstruction. Datasets of the temple surface geometry recovered from point cloud data acquired through field measurements and close range photogrammetry;
- Recovery of Dissections. Close-fit planar dissections reconstructed by correlating raw surface reconstructions from point cloud data;
- Canonical Adaptations. Solid structural blocks and architectural elements are adapted from surface and dissection data to create extruded solid parts for simulation of conjectural reconstruction.

![Fig. 4. Solid Reconstruction Workflow. Surface reconstruction is developed from field measurements and close range photogrammetry. A sparse point cloud is developed using Structure-from-Motion (SfM) technique. A set of horizontal and vertical dissections is developed from the raw point data. Extruded Profiles are used to generate solid elements of the temple geometry.](image)
5.1 Accuracy and Ambiguity: Assumptions

The translation or “reverse” modeling of the temple from existing conditions to a conjectural reconstruction rests on a number of important assumptions. These assumptions are necessary to quantify the accuracy of the translation process as well as address the ambiguities involved in working with deformations and missing information. At one end of this spectrum is the raw model, a direct representation of the current temple as a dense point cloud or surface mesh with textures. The accuracy provided by such an approach is valid in cases where the veracity and integrity of the site is preserved and for visualization. At the other end of the spectrum is a conjectural representation as a three dimensional reconstruction based on primary or secondary sources. This approach is mostly used in cases of insufficient or missing information. Between the raw and speculative representations, lies a number of intermediate or hybrid strategies that seek to combine elements of both and develop a stepwise strategy based on well-founded assumptions. It is this third approach that is developed in this project.

Ground plane and orientation. Establishing the ground plane and the vertical and horizontal axii of the temple using 3-point correlation.

Assumption of symmetry relations. The basic symmetries of the temple are assumed to be regular around the axis. In the case of Kuk Preah Thiet, the entrance doorway and the wall extents are used to fit planar rectangular grids around both axes.

Assumptions of proportional relationships. Manual field measurements are used to scale the proportions of parts and establish proportionate ratios for alignment and fitting of parts.

Structural integrity assumptions. The deformation of the basalt block construction is assumed to be dry wall masonry with a nominal 2 mm joint. The blocks are assumed to be regular cuboids and aligned to fit the assumed orientations in both directions. Offsets are handled with proportionate ratios.

Simplification of element geometry. Complex elemental geometry such as lintels, and doorframes are simplified to regular profile extrusions. Detailed carvings and relief motifs are abstracted to simple profile extrusions.

5.2 Raw surface reconstruction

Surface reconstruction is developed from field measurements and close range photogrammetry (left). The structural blocks are recovered by treating each block as a discrete surface (centre). A sparse point cloud of the object is generated using Structure-from-Motion (SfM) (right). (Figure 5)
5.3 Recovery of Planar Oriented Dissections

Dissections are structured collections of planar two dimensional points, lines, curves and planes that are oriented in three-dimensional space. Drawing upon previous studies of geometry and mathematical schema, horizontal and vertical dissections are developed from an analysis of the sparse point clouds generated using structure from motion. (Figure 6). Dissections provide a new theoretical and methodological bridge to decimate the raw point cloud data and generate the planar, oriented control geometries underlying the construction of temple architecture. In Kuk Preah Thiet, dissections are used to bring together fragments of the raw surface reconstruction, relating these to mathematical and geometric descriptions in canonical texts and proposing “best-fit” constructive and parametric profiles.

Fig. 6. Planar oriented dissections. Raw structure from motion data provides point clouds. The point cloud dataset is oriented to the ground plane and a vertical plumb. A set of horizontal and vertical planes is used to cull the raw point set data. Points are projected using approximation with a threshold value for all points on or near the plane. Regular profile geometry is fitted to the planar points.
5.4 Canonical Adaptations

The setting up of parametric models means that formal relationships might be extrapolated beyond the evidence of deteriorated existing structures, and while this is necessarily speculative, it allows for virtual reconstruction of ancient sites (Figure 7).

6 Results

The digital reconstruction models of Kuk Preah Thiet present new possibilities for interpreting the formal and geometric basis of temple form. (Figure 8)

The computational approaches described in this paper present the creation of stepwise, partial three-dimensional models of geometry recovered from the existing condition survey of the Temple of Kuk Preah Thiet. These models demonstrate:

1. the recovery of the architectural geometry of ruined temples from digital datasets using sparse unstructured point cloud processing;
2. recording the genesis and evolution of the geometric, structural and ornamental techniques used in Kuk Preah Thiet; and
3. Comparative analysis of the complex and problematic linkages between canonical prescriptions of ideal form with the analysis of data recovered from the surviving monument. In particular, the accuracy and ambiguity of geometric reconstruction is addressed in the analysis.

The advantage of this process of stepwise reconstruction is partly a matter of speed, both of data collection and of making geometric comparisons, and partly a new experimental method for interrogating the architecture of the past, focusing on analysis of plans, layout and proportion of wall ensembles, superstructure form and constructional and ornamental motifs.

The results described in this paper recover the geometric basis of this architecture pieced together from diagrams and canonical descriptions, rule-based generation of idealized form models and close-range architectural photogrammetry of temple remains as published in previous work (15-20). The new advances presented in this paper develop early results in the field to identify how large unstructured point sets can be incorporated into the process of analysis and reconstruction following classical models of architectural analysis. As the reviewers of the paper have identified, many of the steps (e.g. Figure 7) remain ambiguous and uncertain, subject to manual and semi-automated and ad-hoc techniques. Formalizing these steps remains the subject of current investigation. For example, the recovery of geometric correlations by algorithmic means by comparing planar dissections will be reported in a forthcoming paper.
The paper attempts to communicate the complex relationships between cosmology, geometry and physical form using computational methods. The program of research is developing both Indian and Southeast Asian models. It is intended that the generative role of geometry within the architectural historiography of Brahminic temples can be clarified and more fully developed. Finally, promoting a better understanding of the potential of these new methodologies to domain experts can significantly enhance the uptake and adoption of computational tools in the rapidly developing area of architectural reconstruction.

7 Conclusion

This paper presents the architectural and compositional connections between Southeast Asian temple architecture using the digital reconstruction of a seventh century stone temple in Hanchey, Cambodia. The digital reconstruction of Kuk Preah Thiet presents new possibilities for interpreting the formal and geometric basis of temple form. This paper presents our research findings on the reconstruction of compositional and architectural linkages from digital datasets of temple geometry. Focusing on the earliest Southeast Asian temples, ongoing research (Datta, 2007; Beynon et al. 2013) is using geometric reconstruction for the comparative analysis of plans, layout and proportion of wall ensembles, superstructure form and constructional and ornamental motifs of the archetypal Brahmanic/Hindu temple. Much of the computational work on point cloud processing has been in the creation of surface meshes, texture mapping and establishing ground truths. To develop these experimental methods into a robust and reliable methodology for architectural analysis, the processing of sparse unstructured point clouds requires new and automated ways of developing plan and section schematics. We have presented one possible way of how this may be achieved in the case of reconstruction from partial information.

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Accuracy and Ambiguity - Geometric reconstruction of a seventh century stone temple in Hanchey, Cambodia


The next city and complex adaptive systems

Justyna Karakiewicz, Mark Burry and Thomas Kvan

University of Melbourne
(Justynak, Mark.burry, tkvan}@unimelb.edu.au

Abstract. Urban futures are typically conceptualized as starting anew; an urban future is usually represented as a quest for an ideal state, replacing the status quo with visionary statement about „better” futures. Repeatedly, propositions reinvent the way we live, work and play. The major urban innovations for the changing cityscape from the last 100 years, however, have opportunistically taken advantage of unprecedented technical developments in infrastructure rather than be drawn from architectural inventions in their right, such as telecommunications, services, utilities, point-to-point rapid transit including the elevator. Howard’s Garden City therefore presaged the suburb, just as Le Corbusier et al proposed the erasure of significant sections of inner city Barcelona and Paris to replace them with the newly contrived towers; the city reformed as the significantly more mobile and dense „Ville Radieuse”. More recently, Masdar emerged from virgin sand and Milton Keynes from pristine pasture, serving as counterpoints to the paradigm of erasure and rebuild. Despite all these advances in technology and science, little has changed in the paradigm of urban form; the choices we have today are largely restricted to the suburban house or the apartment in the tower. Should the “next city” offer an alternative vision for the future, and what new design processes are required to realize the next city?

Keywords: Urban futures, Complex Adaptive Systems, parametric urbanism
A platform for urban analytics and semantic data integration in city planning

Achilleas Psyllidis, Alessandro Bozzon, Stefano Bocconi and Christiaan Titos Bolivar

Delft University of Technology
{A.Psyllidis, A.Bozzon, S.Bocconi, C.TitosBolivar}@tudelft.nl

Abstract. This paper presents a novel web-based platform that supports the analysis, integration, and visualization of large-scale and heterogeneous urban data, with application to city planning and decision-making. Motivated by the non-scalable character of conventional urban analytics methods, as well as by the interoperability challenges present in contemporary data silos, the illustrated system—coined SocialGlass—leverages the combined potential of diverse urban data sources. These include sensor and social media streams (Twitter, Instagram, Foursquare), publicly available municipal records, and resources from knowledge repositories. Through data science, semantic integration, and crowdsourcing techniques the platform enables the mapping of demographic information, human movement patterns, place popularity, traffic conditions, as well as citizens’ and visitors’ opinions and preferences about specific venues in a city. The paper further demonstrates an implemented prototype of the platform and its deployment in real-world use cases for monitoring, analyzing, and assessing city-scale events.

Keywords: urban analytics, semantic integration, crowdsourcing, ontologies, SocialGlass, urban computing, smart cities.
Distributed and heterogeneous data analysis for smart urban planning

Eduardo Oliveira, Michael Kirley, Tom Kvan, Justyna Karakiewicz and Carlos Vaz

University of Melbourne
{eduardo.oliveira, mkirley, tkvan, justynak, carlos.vaz}@unimelb.edu.au

Abstract. Over the past decade, ‘smart’ cities have capitalized on new technologies and insights to transform their systems, operations and services. The rationale behind the use of these technologies is that an evidence-based, analytical approach to decision-making will lead to more robust and sustainable outcomes. However, harvesting high-quality data from the dense network of sensors embedded in the urban infrastructure, and combining this data with social network data, poses many challenges. In this paper, we investigate the use of an intelligent middleware – Device Nimbus – to support data capture and analysis techniques to inform urban planning and design. We report results from a ‘Living Campus’ experiment at the University of Melbourne, Australia focused on a public learning space case study. Local perspectives, collected via crowdsourcing, are combined with distributed and heterogeneous environmental sensor data. Our analysis shows that Device Nimbus’ data integration and intelligent modules provide high-quality support for decision-making and planning.

Keywords: smart city, smart campus, middleware, data fusion, urban design, urban planning.
Tangible mixed reality on-site
Interactive augmented visualisations from architectural working models in urban design

Gerhard Schubert, David Schattel, Marcus Tönnis, Gudrun Klinker and Frank Petzold
Technische Universität München
{schubert, petzold}@tum.de
david_schattel@gmx.de, {toennis, klinker}@in.tum.de

Abstract. The consequences of architectural planning and design decisions made in the early design phases are hard to foresee. While professionals are used to reading plans and understanding architectural models, most laypeople are not familiar with their abstractions. This can lead to misinterpretations and misunderstandings between the different participants in the design process, especially in complex building situations, and decisions can be made or rejected that can have far-reaching consequences for the remainder of the project.

In this paper we describe the concept and prototypical implementation of a decision-support system for the early design and discussion stages of urban design projects that aims to address precisely this problem. The setup directly connects physical volumetric models and hand-drawn sketches with an interactive, mixed-reality visualization presented on a tablet or mobile phone, making it possible to see an interactive real-time view of an architectural design within the context of the actual site. In addition, the system is able to incorporate interactive simulations conducted on the model and presented in the AR-view.

Keywords: early design stages, urban design, HCI, tangible interfaces, immersive environment, simulations
Development of high-definition Virtual Reality for historical architectural and urban digital reconstruction

A case study of Azuchi Castle and Old Castle Town in 1581

Tomohiro Fukuda¹, Hirokazu Ban², Katsuhito Yagi³ and Junro Nishiie²

¹Osaka University
fukuda@see.eng.osaka-u.ac.jp

²Omihachiman City Government
{048200, 390100}@city.omihachiman.lg.jp

³Toppan Printing Co., Ltd.
katsuhito.yagi@toppan.co.jp

Abstract. This study shows fundamental data for constructing a high-definition VR application under the theme of a three-dimensional visualization to restore past architecture and cities. It is difficult for widespread architectural and urban objects to be rendered in real-time. Thus, in this study, techniques for improving the level of detail (LOD) and representation of natural objects were studied. A digital reconstruction project of Azuchi Castle and old castle town was targeted as a case study. Finally, a VR application with specifications of seven million polygons, texture of 1.87 billion pixels, and 1920 x 1080 screen resolution, was successfully developed that could run on a PC. For the developed VR applications, both qualitative evaluation by experts and quantitative evaluation by end users was performed.

Keywords: Cultural heritage, digital reconstruction, Virtual Reality, visualization, 3D modeling, presentation.
Sustainability and performance
The computation turn in structural performance based architecture design

Yongheng Hu

University of Applied Arts Vienna
toto.hu.yongheng@gmail.com

Abstract. It is necessary for an architect to engage closely with structural design, to interpret their design idea thoroughly, and it requires carefully collaboration between architect and engineer. The structural performance based design is not only to obey structure principle but to explore different possibilities of engineer and architectural innovation. Architects could apply this method in the earlier stage of design, and it could provide the efficient solution for structure, create a new spatial experience and further improve the construction quality in the later phase of development. In comparison to structural performance-based design in history, the computational technology has made it possible for architects to implement further the structural knowledge in more dynamic and sophisticated environment. This paper will discuss the history development and current transformation of this method. Three research project will explain the current experimental design process and back the idea of this method.

Keywords: Computational Design, Structural Performance, Finite Element Analysis, Evolutionary Algorithm

1 Introduction

The traditional or the age-old structural performance design method was a hands-off design approach that mainly focused on realizing the requirements of not only the structural laws, but also the structural regulations. As such, for the majority architects, it was difficult to convert their free design forms into construable structures without detailed structural design knowledge. Besides having to seek frequently consultation from the structural engineer, who not only verified and assessed, but also approved designs so as to certify that constructions comply with the setup performance prerequisite.
1.1 Background

With progress in computational force and speedy prototyping technology over the last ten years, a new structural performance-based architectural design methodology materialized. Consequently, Pedreschi highlights this has offered the architects the option to explore the new form-finding technique that could be in projecting the structural performance within the early design stage (Pedreschi 2008). Accordingly, the structural execution of architecture may be simulated, evaluated and enhanced. This has made it easy for architects to work closely together; a factor that has not only helped push the limits of architecture design, but also generating diction between the structural and spatial architectural quality.

Table 1 Diagram of Structure Performance based Architecture History (Yuan & Hu, 2014)
1.2 The Three Eras

From the perspective of an architect, the process of developing a structural performance-based architectural design is usually a nonlinear process comprising of numerous sections and layers.

Chronologically, it may be split into three periods or eras, including the structural tectonic, the graphic statics and the digital morphologies era (Yuan & Hu, 2014).

The graphic statics period started in the 18th century, with the discovery of steel construction and improved concrete technology. This facilitated the construction of curvature buildings, high-rises, and big foot prints by engineers. Consecutively, architects also attempted to delve into the form-finding opportunities offered by the new materials, as well as the modern construction methods. This early form of the structural performance-based method (graphic statics) thus became a significant tool for both architects and engineers to share, collaborate as well as experiment with.

According history, this particular theory was developed by Karl Cullmann. On the other hand, it was his fellow scholars, Müller Bresalu and August Föppl who developed and practiced the method. Müller Bresalu lectured in Berlin while August Föppl lectured in Munich. Alternatively, with increased researchers in graphical statics in English as well as the publications in analytical geometry by Henry Turner in 1874, these particular works came to be widespread in the United States. Afterwards, Professor Lauenstein produced a summary of the findings approximately 100 years back in his “Die graphische Statik” book. His course books can still be located in libraries. Jerome Sondericker, on the other hand, published his book, “Graphic Statics” at MIT, which deliberated on applications to arches, beams and trusses (Jerome, 1903).

As soon as this theory was established, many architects attempted to advance the structural-based architectural design techniques. Rafael Guastavino Jr, for instance, advanced the graphic statics concept to another level by employing equilibrium analysis methods, hence contributing to the graphical study of domes (Fangary & Aly, 2010). Guastavino Jr was among the pioneers to apply innovations in the utilization of graphical methods in not only his design but also construction projects.

Gaudi further advanced the graphic statics concept when he employed it in determining directions of thrusts that spring from the bases of vaults (Torrelles, 2011). Gaudi afterward aligned supportive columns along these lines of thrust, an action that enabled him to evade creating buttresses that he deemed not natural. He thus developed a modern architectural design or style that was not just original, but also simple and artistic. Overall, the engineers’ significant input to architecture, the structural performance-based technique within the graphical statics period, served as an important verification tool for architects to acquire an improved comprehension of structural prerequisites and react to them. They also had vital roles during the structural tectonic period’s structural execution design.

Structure-based architectural design began receiving significant interest during the mid-20th century. In particular, due the rapid progress and reconstruction after the Second World War, the thin-shell construction design began to be increasingly
significant. The thin-shell design has thus had an increasingly significant role ever since the year 1940s. Firstly, the advanced graphic statics structural knowledge facilitated not only the yielding of reliable outcomes from architects, but also made the architects satisfy the structural prerequisites of large civil projects (Asmaljee, 2013). Secondly, the thin-shell design adheres to geometric and clear structural principles. Lastly, it has a cost-effective benefit in terms of the labor resources, the utilization of materials, and the construction period has been cut to the least.

The concept of framing social interaction also offered architects with an opportunity to carry on probing the historical lineage or bases of design research within the physical form-finding domain, including the soap films, the hanging chains, among others, which were pioneered by individuals such as Felix Candela, Eladio Dieste, Frei Otto, and Heinz Isler, and others. Nonetheless, there were debates regarding this particular method (Kotnik & Schwartz, 2011). To begin with, this particular method was argued to be producing unique outcomes that are not repeatable. However, this inadequacy in terms of the number of repetitions of experiment could result in unwanted outcomes. Furthermore, individuals argued that these designs were being generated in exceedingly defined ways, a factor that is argued to lower creativity of the design process. Finally, there were arguments that these particular methods only offered a limited number of outcomes. As a result, making it problematic for architects to obtain not only potential structural or artistic solutions and optimum materials. These particular shortcomings have driven architects to seek not only new tools and technologies but have also improved the design methods.

Alternatively, during the digital structural performance morphologies period, it became significantly fundamental and indicated prospects, besides its analytical value that goes beyond its instrumentality. The graphic static model has, on the other hand, been converted into algorithms. Consequently, architects could now have a better understanding of this particular long-established structural analysis, which could not only assist them improve structures, but also attain improved structural performance with an economical budget.

Architects also advanced it into a form-finding tool so as to produce high performance as well as create adaptive and dynamic structural systems. Moreover, it offers solutions for the new algorithmic design including agent-based design practices aimed at finding significantly sophisticated as well as adaptive/flexible structural solutions to the hyper-complex geometry. For instance, the finite element method helped an engineer such as Mike Xie and an architect such as Mark Burry to decrypt Gaudi’s mystifying geometric design as well as comprehend the construction works of Sagrada Familia. The topological optimization model, on the other hand, acted as an inspiration to architects such as Panagiotis Michalatos who manufactured software such as the Millipede plug-in and BESO used by architects to help them understand the topological optimization concept at the start of a design process.
2 Research Projects

To explain the development of computational design in structural based architecture design processes, Three research project will describe the current experimental design process and back the idea of this method. Firstly the multiple objective optimization could be achieved by setup design domain in the computer-aided design environment and with the help of algorithmic computational design tool, as a result, a flexible and optimum result could be developed. The second projects show a potential of escape from the static architecture structure and introduces dynamic balance in space, with the help of computational simulation and analysis. At last the research will explain how could this method improve the constructability and performance of algorithmic design that create complex geometric space such as agent-based architecture design.

2.1 Multi-Objective Optimization

The initial design purpose was to create additional space for extension of an existing building (Fig. 1). The extended space is formed by a planar grid that pushes out of the current facade. An evolutionary algorithm is used to attempt to maximize the volume enclosed by the frame, and the finite element method would help to ensure the structure can support the load. The input parameters specify a 2-D regular triangulated truss system with six members connecting at each joint.

The overall structural form is generated in response to a model input by the user and can be adapted to individual design scenarios. It optimizes both the topology and geometry of a structure by minimizing the design objectives, e.g., material quantity for the given loads, while respecting the constraints. This is conducted in 3D environment of Rhinoceros with the help of the FEA optimization method (Roylance, 2001) and the Pyevolve, a Python Evolutionary Optimization Library (Perone, 2009) which has been import in Rhino Python. This project also aims to minimize member lengths while meeting all geometric constraints and to maximize the volume enclosed by the frame while meeting all geometric constraints.

The constraints of this projects are: Base points (the joints that need to connect to the existing building), the spatial limitations (maximum height, boundary lines,
maximum cantilevered distance), the maximum number of members meeting in any one joint, the maximum and minimum lengths of each member, and the minimum angle between two members at any one joint. This design referenced these constraints as a starting point of overall structure generation.

The genetic algorithm is guided through all the steps of its process by an objective function. The fitness function that depicts the dynamics of genotype frequencies in a population for reproducing individuals, quantifies the prospective for the survival of any individual. A fitness value for a chromosome determines its optima in order to be ranked against all the other chromosomes in a population. The fittest chromosomes are those that are allowed to participate in the genetic process, producing a new generation that will be better (Fig. 2). The definition of the fitness function is not always a straightforward task, and there are cases for which it is quite difficult to come up with an absolute fitness function that will lead to the optimal solution. In this research project, the process was not always direct, but it was always goal-oriented: to reach the point where the tetrahedralized space frame with randomly distributed joints will perform as well as an engineered structure on an orthogonal canonical grid with the same number of joints. Towards that end, a couple of different fitness functions were experimented with, endeavoring to achieve the best results.

The basic rule of the algorithm calculation is a regular grid system. The selected planar surface or mesh should be divided into regular sections as shown; identical faces will be formed through the division (Fig. 3). In Python scripts, a loop is needed to get the faces of the picture and append them to a list. Several points need to be extracted from the faces: the starting and the ending points of the mesh/grids, all joining points, and the midpoint of each division.
The vertices of the mesh are decided by the starting point that will be determined by the user. For this reason, the mesh could be formed through two parameters: faces and vertices. Each point will be assigned three parameters: X-coordinates, Y-coordinates, and Z-coordinates. Paths of the nodes along Y-Z plane will be limited according to the set rules that then will be applied to the scripts in order to solve the overlapping problem.

2.2 Dynamic Equilibrium Optimization

Located at London Canal riverbank, The Buffer-Zone house is a project that attempts to tackle the problem of modern dwelling architecture’s conservative static lifestyle and radical detachment from nature (Fig. 5). Enabled by a contemporary structure optimization method and construction technological solutions such as the pre-stressed tensile system, the house itself aims to blur the boundary between nature and living space, to create a more dynamic-balanced, unexpected, and reconnect nature with living experience.
Torsion of Domino House: After analysis, arguably the primitive model of the modern house, the prototype that was designed by Le Corbusier, the structural problem of torsion has become the central focus of this design. Torsion, in many cases, is the main latent hazard in extreme natural disasters, such as earthquakes and flooding, as is foundation erosion (Fig. 6.1). It will cause structural distortion and even structural collapse. The main cause of this is the geometry centroid and structural center of buildings are not at the same location.

Torsion Orientated Optimization: Through a torsion-reduction orientated optimization, the structure of the house turns to a compound system and the spatial condition of the house turns to a continuous spiral for the movement (Fig. 6.2). Also, the twisting effect of torsion generates spirally helicoid geometries. Thus, we decide to drive the helicoid geometry and composite structure member and circulation together to counter torsion and provide continuous movement. To strengthen the overall result, the handle geometry was introduced to provide natural light and encourage interaction between different levels.
Helicoid Geometry: Empowered by a pre-stressed tensile system, the structural envelope of the house becomes a non-standard, open-air, tightly-wrapped, tensile structure consisting of opaque pre-stressed carbon rods. Guided by pre-stressed tensile system joints, the rods connect with each other and all the way to the ground. Through connecting and bonding the rods with the top of core building structure with pre-stressed tensile system fittings, the load is continuously transferred through rods, and then the loads are distributed to the ground (Fig. 7). The pre-stressed rods provide sufficient structural support and helicoidal reinforcement for the overall geometry; at the same time, they also refine the quality of the helicoid geometry and create a blurred and soft yet dynamic balance for the building facade.

Feather-skin Facade: The bird feathers display the possibility that, by closely arranging special thin line elements, the skin could have waterproof features and, at the same time, remain breathable and transparent. In this case, the ETFE thin line has made it possible for the facade to breath and prevent humid site conditions. Sewed with structural fabric and bundled at a very close distance, the ETFE lines fit around the exterior rim of the house (Fig. 8). The pre-stressed tensile system makes it possible to control the ETFE thin line system by guiding and locating the structural fabric.
The boat and house are extensions of our movement and play important roles as spatial changing agents (Fig. 9). In different situation of car and boats the movement of building become varies.

2.3 **Swarm Intelligence Optimization**

It is important for agent-based architects to reclaim their right by applying a workflow that is more responsible for construction and the structural performance of the design. Many existing workflows only focus on post rationalize the structural computation (Hu and Li, 2014). As a complete solution to the practical problems, it’s necessary to include pre-assessment, structure assignment, and post-optimization in this workflow (Fig. 10).
Pre-assessment acts as a rationalization process before the agent-based computation runs. In many cases, an agent-based architecture’s structure can be rationalized into a structure primitive, which is the combination of several key structural features. Pre-assessment in the early design stage is defined with basic structural ideas that could inform structural properties in the process of agent computation (Fig. 11). Furthermore, this helps the agent-based architect design a rational structure in the first place, which provides possibilities to maximize the freedom of design. Also, in later stages, it shifts to a structural tool that is able to provide an accurate analysis. This dual-stage method, which is not all-inclusive, prevents architects from overcomplicating structural setups in the processing, as many others attempt. The pre-assessment includes pre-setup, process-bundling, and pre-analysis. The agent setup should include pre-setup at the same time, such as supports, attachments, and base points before the agent generation process begins. The process-bundling is a process of agent simplification, and there are many existing algorithms to choose from. Lastly, the pre-analysis take place by analyzing the structural rebuild in the Rhino Grasshopper Environment. In the case of the above project, the original design is preset in the processing; the supports and attachments are placed according to the existing context. In the run agent process, the design agents lines are bundled, and a preferable design is chosen. In the later stages, the extracted lines were used as reference for rebuilding a spatial surface to accommodate the agent design result. In the analysis, the mesh was rebuilt as the overall structure in Karamba, an FEM-based structural plug-in for Grasshopper. The pre-analysis result shows that few cantilevered parts of the space have structural problems. The maximum cantilevered part is 30 meters. Through calculations, the maximum displacement of this design is 0.24 meters.

Derived from the previous step, the result of agents based on process and structure information could be used as a starting point of structure assignment. Structure assignment ensures a precise simulation of one or multiple structure types, materials, and elements. Thus, improving the feasibility and even providing cost control for the final result. The characteristics of a defined structure type and material give rise to various constraints in the construction process. These constraints are often neglected
in the agent-based design process which may cause unreliable results. In the workflow, the structural, material properties, and even construction methods (such as optimizing, controlling, and reducing variation of elements and standardizing elements), are taken into simulation via converting them into geometric constraints, and so-called line and shell models in the structural analysis engine, as in Karamba. In this case, the main structure type has been chosen as 3D spatial steel frame structure, and steel has been chosen as the main material.

The structure has been built based on the agent-based line model. The extent of beam types, such as hollow beams, I-beams, and circular beams, is surveyed through experiments in the computer model (Fig 12). After selection, the specified material type, profile type, and structure type has been carefully inputted into the structural performance model and started to regenerate different structure models.

After choose desirable settings, the next step is controlling the number of structure members. The range of sizes has been narrowed down to achieve optimum construable results, and the variations of elements have been optimized to find a balance between better structural performance and minimizing construction costs. As we can see from Fig.13, the different sizes of beams are applied to the model. The first one creates highly differentiated models that kept the most properties of agent-based models, but the 30 different sizes might need more cost infusion and joint types. The last one is the most economically efficient one, but the model is relatively too standard. Thus, the good solution is the one in the middle which allows for a limited number sizes of beams and balancing between cost and performance.

The process of the structural assignment takes the form of transforming structural behaviors of the actual structure, material and construction features into their corresponding behaviors in the computational structural engine.
After previous processes, the well-established structural performance-based model has been set up. The advanced tool, Karamba developed by Clemens Preisinger in cooperation with Bollinger-Grohmann-Schneider ZT GmbH Vienna, enables architects to step further and make more detailed optimization of the structural frame. Post-optimization includes the visualization and data management of the preceding result. It’s helpful for the agent-based architects to evaluate the quality of the space and structural result in seeking the solution to the construction issue. As a complete set of solutions, the visual feedback of the structure properties of the design is reflected in the present process (Figure 14), as well as some engineering related to structure drawing such as numbering and dimension. It’s also possible to export the statistical contents of the structure model to many different formats of structural analysis software, and it will be very advantageous for the structural engineers to design according to agent-based architects’ requirements.

We could analyze, optimize, and solve a more specific structural and spatial design issue. In the example, the large cantilever parts have been optimized, and the structure has been enhanced to keep the original large-span, no-column space. This creates the necessary space for specific programmatic requirements such as auditorium and theatre space. More importantly, the structural informed space articulates structure ornament and function together, finally achieving the quality that agent-based architects desire.

We use a two-structure system to support an agent-based space: the traditional beam and column system and the structural performance design system. The two sections above present two entirely different space effects (Fig. 15). The traditional structural system limits space division and encroaches on the design’s initiative with elements that can stretch vertically and horizontally only. The structure also becomes a passive appendage to the building’s shape. The most typical disadvantage is in large-span spaces.
3 Conclusion

At the outset, the structural performance-based design method advances and uses not only the computational techniques, but also the digital construction technologies in order to develop the inherent structural characteristics, as well as specific underlying performative capacities. By developing the structural systems, embedding their material qualities, their geometric behavior, assembly logic and manufacturing constraints within a computational model, the systems operation can be assessed vis-à-vis structural performance. Developing the structural systems also offers opportunities to reconsidering the predominant efficiency notion through the efficacy of the structural systems.

Secondly, the structural performance-based method neither employs the use of form-active structure primitives as the major design drivers nor the structural behavior properties as its established form-finding tools. However, it creates a new kind of between the architects and engineers; as a result, facilitating architects to design a multi-objective form-finding process through numerous hierarchies that describe complex/multidimensional architectural systems (Yuan & Hu, 2014). The structural performance optimization enables the design to be adjustable and more responsive. The performance-based innovative synergy outcomes materialize from its greatly differentiated morphology utilized with this particular method.

Lastly, the structural performance-based method is basically a method that facilitates or allows architects to have a more significant as well as an engaging task (role) in as far as the rationalization and execution of a multifaceted geometrical structural design are concerned. Alternatively, it also facilitates the improvement of
project performance by architects. More significantly, however, the structural
performance-based method could be employed by architects as means through which
they can develop new forms so as to articulate structural members and structural
space (Schumacher, 2014).

As such, we can argue that this particular method seems to be a requirement for not
only building design methods, but also techniques aimed at form realization. It is
actually meant to elaborate new possibilities in terms of designing new forms, as it is
capable of articulating not just space, but also materials, social requirements, and
architectural information with a significantly higher performance level than earlier
possible.

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Sketch-based and parametric modeling

Association of two externalization processes for early daylight optimization

Mohamed-Anis Gallas\textsuperscript{1,2}, Vincent Delfosse\textsuperscript{2}

\textsuperscript{1} School of Architecture of Nancy  
\textsuperscript{2} University of Liège  
{ma.gallas, vincent.delfosse}@ulg.ac.be

Abstract. This paper focuses on sketch-based and parametric modeling as two externalization devices used in architectural design practice. The first part of this paper addresses features and ability of these externalization tools to support design activities during the early design steps. The second part proposes an association process of a sketch-based modeling tool (SketSha-Archi\textsuperscript{®}) and a parametric modeling tool (Grasshopper\textsuperscript{®}) to create an advanced process for daylight optimization. The process aimed to associate the hand-sketching freedom with the precise exploration functions of digital tools (parametric modeling and evaluation tools).

Keywords: Sketch-based modeling; parametric modeling; early design stages; daylight simulation; optimization process.

1 Parametric modeling in architectural design

Parametric modeling is one of the digital modeling methods integrated in architectural design praxis. The generated models are controlled by parameters that characterize and control the most pertinent features of the modeled object and the design context. Parameters can describe geometric, performance, structural, material, social, urban and environmental features. The designer can generate different spatial and technical configurations based on the same parametric model. Parameters are instantiated by interchangeable values generating these objects.

The designer controls the value attribution process and try to find the best response to the design intentions and constraints. Optimization algorithms can be used to control the parameters instantiation process. The designer defines a target values describing his intentions (features, performance) translated in measurable values and optimization algorithms controls the value attribution process. These algorithms select the best parameters values generating the most pertinent configurations (verifying the target values). Evaluation devices linked to the parametric models to compute the performance level of the generated solutions [1], [2]. The evaluation devices concern sensitive features (atmosphere) and physical ones (daylighting, energetic and...
structural behavior). The association of parametric model, evaluation devices and optimization algorithms creates an iterative process that helps designers to operate complex research and exploration design activities. This kind of process contrasts with the static behavior of the classic modeling methods that are used to create one instantiated model. A fixed statement and a complex modification process characterize the modeled objects. In contrast, parametric modeling methods are used to define the structure of the designed object and the most pertinent controlling parameters in order to generate different configurations. In fact, the dynamic features of the parametric modeling methods offer more exploration potential than other digital modeling media [3].

As explained before, parametric modeling methods define the structure of the modeled object and not a fixed status. Object status will change depending on values attributed to parameters. A parametric model easily integrates transformation and evolution activities. During the early design steps, designers try to explore possibilities define the most important project features. At the beginnings, these features are fuzzy and hardy measurable due to the lack of design information. They progressively evolve to be more precise thanks to the iterative process of propose, evaluate and select activities. These features make parametric modeling methods more suitable for early design activities [4].

Parametric modeling is an evolutionary process. It can be transformed and enriched progressively as design process progresses. The designer can transform the parametric model structure by integrating new parameters, new features and more functions. The parametric model can be linked to more detailed ones adding new functions resulting from more advanced design steps. The following example shows how the designer used a parametric modeling tool (Grasshopper®) to design the lofted surface creating the outside skin of the project (early design steps) using simple curves. The model has been improved to integrate the skin materialization process using two modular components types (advanced design steps). The modular components are dispatched on the created surface through a distribution condition. The designer used the same model to integrate his early and advanced design intentions and constraints.
During the early design steps, designers spend from 5% to 20% of their designing time to create the parametric model. The duration of the modeling and transformation time task depends on the knowledge level from of the parametric modeling tools. Expert users reduce duration required for the definition of their parametric model definition and allow more time to perform design activities. By contrast, novice users of parametric modeling tools consider modeling activity as an additive design constraint that constitutes an additive cognitive constraint. This constraint can delay the design task achievement.

Fig. 1. Evolution of the parametric model [5]
We consider parametric modeling as an advanced externalization activity that respects the early design steps features. This activity needs to be improved in order ease the parametric modeling activities. Parametric model creation must respect the designer’s praxis by generating design media in few laps of time. Support design models (parametric models) must be easily transformable and particularly for conceptual steps.

2 Sketch based modeling in architectural design

2.1 Sketching in architecture

Sketching, as a representation tool, help designers to externalize their intentions and ideas and to address a first step of graphical conceptualization for architectural solution [6]. Sketching is considered as a tool to simplify reality, illustrate intentions and going to the most pertinent concepts [7]. They help the designer to progressively materialize design problems and reduce their complexity. Sketching helps designer to quickly produce and modify representation of the design problem and solutions [8], [9]. The use of sketching creates an iterative process of design integrating “propose”, “evaluate” and “modify” activities. The iterative features of this process ensure the flexibility of the modification and appropriation activities characterizing early architectural design steps [10]. The flexible structure of sketching generates multiple interpretations of the externalized ideas and solutions through a continuous reflection process [8].

The precision level of the representations and the models increases and accompanies the evolution of the design activities. Written data and conceptual sketches and models are used during the early design steps characterized by the lack or the inaccuracy of the design information. Detailed representations, physical and digital models are usually used during the last steps of the design process where design information is available and precise. Representation tools like sketching used at the early design steps as sketching enhance the designer freedom. They allow many options and opportunities for how they can be read and understood [11].

By contrast, the use of digital modeling tools during conceptual design steps reduces the designer freedom. This limitation is due to the use of new artifacts.
Sketch-based and parametric modeling: Association of two-externalization processes for early daylight optimization

(screen, mouse), new gestures, the need of detailed design information and a longer realization time. Despite this limitation, digital design tools, initially destined to production steps, are now used in the early steps. These steps are characterized by research and exploration design activities. The use of production design tools during early design steps tends to reduce the designer creativity and to impoverish the design. The designer is influenced by the tools functions during the decisive steps of the project elaboration [8]

2.2 Sketch-based modeling

This observation has led to update sketch-based modeling technics integrating gestures in modeling process. They associate free hand-sketching functions to digital modeling ones. This technic was initiated since the sixties by Ivan Sutherland that develop the Sketchpad device [12]. This device proposes a graphical freehand interface to draw geometries. It aims to associate the benefits of hand drawing to the digital tools functions.

Since 2007, the LUCID-ULg has been developing and using the SketSha® software (for Sketch Sharing) [13]. This application supports sketch-based, synchronous and distant collaboration. Based on the analogy of a real meeting, SketSha® offers a shared working space, where all participants can import and annotate any design documents (image, pdf, dxf or screen-captures). This application has been discussed in many articles [14],[15], [16]. The figure below shows an example of a SketSha® project.

![SketSha® interface and use](image)

Fig. 3. SketSha® interface and use

Sketches are also used to generate 3D models. They are used as basic information for complex 3D modeling activities. They allow user to draw free hand sketches and to translate them to tangible 3D models using digital pens as communication and expression artifacts. The generated models can be used for representation purposes or can be integrated to the evaluation processes. The translation of 2D sketches to 3D models is achieved in three steps; a sketch analysis step, a synthesis step and an interpretation step. This process is limited by the need of precise knowledge about the design context and the used representation rules.
An alternative solution was integrated in SketSha®. An architecture-specific version has been developed. It allows the generation of an architectural 3D model, based on some explicit drawing conventions used in the sketches. It uses dedicated pens to describe walls, windows and doors. These elements will be extruded vertically in order to produce a 3D model. The figure below shows an example of some mix of interpreted and non-interpreted 2D layers and the resulting 3D model. Tagging the concerned layer (red tag on the layer name) activates the 3D interpretation process. We associate a semantic dimension to the sketching tools (pens) describing the most important parts of project as wall, bulkhead, windows and materials. We need also this information during the evaluation process of the project daylight behavior. This process simplifies the analysis step and enhances the adaptation ability to different design context and users.

![Fig. 4. Multiple layers of 2D sketches and the resulting 3D model](image)

The tool supports multiple floors and the user can control the heights of the different floors, doors and windows on a per-floor basis. SketSha-Achi® also allows some more complex extrusion capabilities, useful to express non-flat roofs for instance. One of the sketching pens is dedicated to design draw and characterizes the roof edges. The roof generation tool analysis the drawn edges to propose a 3D interpretation. The figure below shows the roof edges drawing process and the generated result of a multiple sloped roof.

![Fig. 5. An example of complex extrusions producing a roof](image)

SketSha-Archi® allows many layers to be placed on top of each other and visualized through a controlled transparency. The designer can define which layers
will be part of the 3D model, and which layers are just pure 2D annotations. This mixing of interpreted and non-interpreted layers enables a two-step process for a design iteration. The user can freely explore his design ideas with non-interpreted sketches. Then, when the project reaches the required level of maturity, the user can create the interpreted layers, and overlay his previous sketches with the interpreted pens. The user can decide whether the 2D sketches are displayed in the 3D view or not. The generated model must be integrated in the design process to develop and enhance the performance and features of the proposed solutions. It must be used as a base line model to operate exploration and optimization activities.

The generated models are unique with fixed characteristics. The modification process of the generated models needs a major intervention of the designer (the use of modeling tools to modify the model features). This cognitive load reduces the possibilities to integrate the generated models in an iterative optimization and evaluation process.

Fig. 6. Sketching, 3D model generation and evaluation process

### 3 Association of sketch-based and parametric modeling

#### 3.1 Association process

We propose a design aid strategy to help the designer to externalize his ideas and to explore potential solutions during early stages. The method aims to keep design freedom characterizing sketching steps and to propose a solution to associate complex activities (evaluation, modification and optimization) to these steps. This strategy associates the interactivity of sketch modeling methods and the exploration ability offered by the parametric ones. We consider them as two externalization devices able to support design activities during the early steps of design process operating at different levels of accuracy. Sketch-based modeling methods will be used to materialize ideas (free hand sketching) and to translate them to 3D dynamic models (translate sketches to parametric models) able to operate exploration and evaluation activities. The association of the sketch-based and the parametric modeling methods
creates an iterative process of “propose, evaluate and modify” activities. The designer uses this process to operate an optimized process of architectural and technical solutions generation verifying a given targets.

**Fig. 7.** Association process of sketch-based and parametric modeling methods for evaluation and optimization purposes

### 3.2 Advanced sketch based modeling process

Evaluation and generation activities need detailed design information. These information concern the project features participating the optimization process. For daylight behavior optimization process we need detailed information about project as wall reflection factor or aperture transmission one. We propose to associate these semantic information to the drawn sketches. Designer can characterizes the designed project by a drawing colored strokes on the drawn object. These strokes will be interpreted as extra-information to be transferred to the parametric tool. The exact semantic of this information is not embedded in SketSha Archi®, but is left to the user and to the parametric tool itself. Designer can change the signification of the different tags to associate them to new features or new kind of materials depending on design context.

**Fig. 8.** Illustration of some added information to the building description

The figure below illustrates the possibility to add extra information to the building. The window in blue is tagged with a green stroke, when the wall itself is tagged by a
single purple stroke. The designer can decide on the semantic signification of these tags. For instance, the green tags represent 10% of opacity. The user can then adapt the level of opacity of this window by adding or removing green strokes, thus changing the properties of its element without leaving the 2D graphical interface.

A specific file format has been developed for exchanging data between the sketching and parametric modeling tool (integrating evaluation and optimization devices). It is a text-based file in order to ease its parsing in the parametric-tool side. It contains all the information of the geometric 3D model, the semantic of the elements (wall, doors, etc), as well the tag information. The export file is structured by keywords describing the geometric features of the exported project and the associated annotations. Keywords describe the project from a global scale to a detailed one. It detail the number of floors composing the drawn project, the height, the wall count and the created space count for each identified floor. The keywords concern also the geometric features of the walls, the windows and the doors composing the different spaces. We mean by geometric features the number, the type of segments used to represent these objects. The keywords are also used to identify and describe the design information associated to the project objects and particular the tags count and types.

For instance, for the top-most wall in figure 11, the full wall is described with both the green and purple tags. Then its 3 sub-parts are described, as 2 walls and 1 window, each coming with their specific tags.

```plaintext
Floor_count-1
Floor-0
  Height-3
  Wall_count-4
  Space_count-1
  Wall-0;
    Segment_count-1
    Segment
      w.Annotation_count-1
      Annotation_magenta
      Polylime;
        w.Point_count-4
        25521.44,24640.05
        25523.0,24661.0
        25525.0,24896.0
        25503.66,25475.05
      Wall 1;
      Segment_count-3
    Segment;
    w.Annotation_count-1
      Annotation_magenta
```
Polyline;
  w.Point_count-3
  25503.66,25475.05
  25296.0,25485.0
  25225.0,25483.58

Fig. 9. Example of exported file from SketSha Archi® describing a sketch

3.3 From sketches to parametric model

The generation of the parametric model and the evaluation process are implemented in a Grasshopper® definition. The generated 3D model integrates the project volumes, opening faces and windows. We create a Grasshopper® definition to read the export file generated from SketSha Archi®. It retrieves the information used to create the parametric model components (walls, apertures) and their features (roof height, aperture dimension). These information are integrated in Grasshopper® components that generated the different geometries (polygonal surfaces).

Tags are also used to identify annotations associated to the model components and translate them into features characterizing the generated model (aperture and wall material).

Fig. 10. Parametric model generation

The designer can modify the feature of the generated model. We associate four parameters to “roof”, “window” and “orientation” keywords. Designer can attributes new values to these parameters modifying the generated model features. By this way,
we create two modification scales. The first one (global scale) concerns the sketches initially used to generate the 3D model and the second one (more local) concerns the model components.

The parametric model is used to initiate an optimization process of the quantitative and the qualitative features of the designed project. This process integrates the plugin Diva For Rhino® [17] that links Grasshopper® to the daylight simulation software Radiance®. The optimization algorithms control the parameters value attribution process and operate to find a target defined by the designer. We use an image (representing daylight effects) selection process to identify and characterize the designer daylight intentions. The characterization (quantitative one) of the identified daylight intentions constitutes the target function used to operate the optimization process. This identification and characterization process is a result of my precedent research work [18]. We use Galapagos® as the optimization algorithm associated to the Grasshopper® and Diva For Rhino® as simulation device. We define the number of simulation nodes to reduce the optimization process duration to less than 10 minutes. This duration respects the design activities and process features.
The parametric model is generated from digital sketches in a short amount of time. The automatic generation process helps the designer to simplify the parametric modeling activity and to quickly initiate an optimization process. These features allow the integration of optimization activities during the early design steps. The user can use his sketches to explore other spatial configurations and solutions using the same generated parametric model. The parametric model can be modified and updated to integrate more precise design information or parameters values (other materials, aperture features).

![Image](image.png)

Fig. 12. Evaluation and optimization process

4 Conclusion

This paper presents a design method integrating sketch-based and parametric modeling tools for daylight optimization during early design steps. We consider sketch-based devices as a first externalization method respecting the designers praxis. Parametric modeling devices are considered as advanced externalization method integrating precise and controlled optimization activities.

The design method was implemented using a sketch-based modeling tool (SketSha Archi) and a parametric tool (Grasshopper® definition) integrating a simulation tool (Diva For Rhino®) and an optimization algorithm (Galapagos®). Experimentation results shows that the process can support the design activities during the early design steps but needs some improvements. We are now working on the generation of complex parametric models and the ability to integrate more designer intentions and design constraints.

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Interrogating interactive and responsive architecture
The quest of a technological solution looking for an architectural problem

Sara Costa Maia and Anna Lisa Meyboom
University of British Columbia
sara.maia@alumni.ubc.ca, ameyboom@sala.ubc.ca

Abstract. Interactive Architecture and Responsive Architecture are provocative fields of investigation and have potentially disruptive and far reaching effects for architecture. However it can be argued that these fields haven’t been developed as a direct response to previously identified architectural demands. Instead, they have risen as consequence of new technology availability, with ad hoc discussions in the context of the built environment. In order to test this hypothesis, 229 publications were examined and narrowed down to 77 papers and 41 design projects, which were systematically analyzed. The primary objective of this investigation is to understand Interactive Architecture’s development with regard to justification. This understanding provides us with the basis to speculate on the possibly expanding introduction of extraneous technological solutions to the discipline of architecture. The research findings indicate a mismatch between theoretical discourse and projects being developed in those fields. They also describe the current state of Interactive Architecture research.

Keywords: Interactive Architecture, Responsive Architecture, Literature Analysis, Design Projects Analysis.
A model for sustainable site layout design of social housing with Pareto Genetic Algorithm: SSPM

Yazgı Badem Aksoy, Gülen Çağdaş and Özgün Balaban

Istanbul Technical University
yazbadem@hotmail.com, cagdas@itu.edu.tr, ozgunbalaban@gmail.com

Abstract. Nowadays as the aim to reduce the environmental impact of buildings becomes more apparent, a new architectural design approach is gaining momentum called sustainable architectural design. Sustainable architectural design process includes some regulations itself, which requires calculations, comparisons and consists of several possible conflicting objectives that need to be considered together. A successful green building design can be performed by the creation of alternative designs generated according to all the sustainability parameters and local regulations in conceptual design stage. As there are conflicting criteria's according to LEED and BREAM sustainable site parameters, local regulations and local climate conditions, an efficient decision support system can be developed by the help of Pareto based non-dominated genetic algorithm (NSGA-II) which is used for several possibly conflicting objectives that need to be considered together. In this paper, a model which aims to produce site layout alternatives according to sustainability criteria for cooperative apartment house complexes, will be mentioned.

Keywords: Sustainable Site Layout Design, Multi Objective Genetic Algorithm, LEED-BREEAM.
Algorithmic design tool for integrating renewable energy infrastructures in buildings

Object Oriented Design for energy efficiency

Florin C. Popescu
Fraunhofer Institute for Open Communication Systems
Florin.popescu@fokus.fraunhofer.de

Abstract. We present a tool which empowers 'green' design freedom for architects by presenting ever expanding choices in components and materials and automatizing their configuration and placement. Several time- and resource-consuming initial design iterations are eliminated by optimizing the energetic efficiency of the building in the original draft phase. The smart, efficient, energy producing building of the future can thereby offer increased cost and energy efficiency, security and comfort, without any compromise in style and form - on the contrary, the proposed tool stands to open up a novel palette of creative 'green' architectural design elements, which would effectively be co-designed by architects. The proposed algorithmic CAD design tool allows direct integration of renewable sources in the architectural design phase, taking into account local meteorological and solar radiation conditions. Furthermore locally optimized evolution and modification of renewable components integrated into the building's structure is possible, leveraging an increasingly wide range of possibilities in form, finish and renewable energy generation.

Keywords: Algorithmic and parametric design, data analytics, performance-based design, smart buildings and smarts cities.
Pedestrian as generator
Implementing a stand-alone piezo power generating device in the urban context

Elena Vanz and Justyna Karakiewicz
University of Melbourne
{elena.vanz,justynak}@unimelb.edu.au

Abstract. During the past decade the implementation of energy harvesting sensor technology, at micro scale, has occurred due to the rapid growth of low-powered device usage, such as mobile phones, laptops, and the development of LED lights significantly increasing in efficiency. Studies have demonstrated that the ability of this technology to harvest energy from the human body, such as footfalls, can be used in the generation of electricity. Piezoelectric sensor technology has been investigated for this purpose, due to its significant advancement in the efficiency and its application in a variety of designs. This research investigates how pedestrians can become generators of their own service, through the use of piezoelectric sensor technology, in the form of safety lighting. Proposed urban design scenarios explore the opportunity implementing a piezo power-generating device along high traffic pedestrians pathways in the City of Melbourne (Australia), evaluating real time and storage options, considering harvesting the energy during the day and using it at night time when needed.

Keywords: Piezoelectric sensor technology, micro-scale distributed generation, public space.
Dynamic façades and computation
Towards an inclusive categorization of high performance kinetic façade systems

Rodrigo Velasco¹, Aaron Paul Brakke² and Diego Chavarro¹

¹Universidad Piloto de Colombia
²Whiteknee
{rodrigo.velasco,aaron.brakke, diego.chavarro} @gmail.com

Abstract. This chapter provides a panorama of the current state of computationally controlled dynamic façades through a literature review and a survey of contemporary projects. This was completed with an underlying interest in understanding how innovative design solutions with the capacity to ‘react to’ and/or ‘interact with’ the varying states of climatic conditions have been developed. An analysis of these projects was conducted, and led to the identification of tendencies, which were subsequently synthesized and articulated. While most classifications are limited to describing the movement or structure needed to achieve morphological transformation, an important recommendation is to also consider control as a determining factor. For this reason, the culmination of the investigation presented here is a proposal for a classification structure of dynamic façades, developed according to the functional modus operandi of each structure in terms of movement and control.

Keywords: Dynamic Facades, Kinetic Architecture, Computational Control, High Performance Building Envelopes
Automated and parametric design
Analysis of space layout using Attraction Force Model and Quadratic Assignment Problem

Gozdenur Demir
Istanbul Technical University
gozdemrg@gmail.com

Abstract. This paper researches the usefulness of computerized space layout programs in an actual problem of space layout of more than 50 design units of unequal sizes. This was tested with two existing space layout optimization methods, Quadratic Assignment Problem (QAP) and Attraction Force Model (AFM) as well as a satisficing method, intuitive approach. Necessary inputs for the evaluation processes, the evaluation processes and the resulting space layouts were analyzed for each approach by one designer. Their performance in the design process was criticized on subjects like preparation of inputs, situations related with multiple trials, evaluation of the resulting space layouts based on given inputs and what those space layouts represented. Generating alternatives is an advantage of computerized space layout approaches so that conditioning on the resulting space layouts decreases in the process but more research has to be done for their practicality in terms of input preparation, evaluation and transfer of outputs. Possible improvements were suggested to increase their usefulness in the professional field.

Keywords: computerized space layout approaches, quadratic assignment problem, equilibrium method, intuitive approach

1 Introduction

Space layout is a complex architectural problem because of the interdependent structure of individual design objects and the vast number of solutions even with small sized problems. Researchers have been approaching to this complex problem with different methods for almost 60 years (Koopmans, Beckman, 1957).

The initial critics on the performance of the computerized space layout approaches were published in around 1975 (Scriabin, Vergin, 1975). The recent publications in the literature are based on the weak interest of companies and architects to computerized space layout approaches. This research was done to contribute in the literature by exposing the performance of the computerized space layout approaches in an actual design process and seek for the possible reasons of the disinterest of the architects in them.

Different programs were developed for the problem of space layout using different approaches both in commercial or academic use (Canen, Williamson, 1998). The
search for the model used in the design process was based on its capability to handle space layout problems greater than 50 design units of unequal sizes. Additional requested criteria were to optimize adjacency relations, to work in 2D, to be available and to be user-friendly. In this regard, two models, QAP and AFM were selected because of their basic representations, ability to deal with large size problems and availability.

QAP is formulated as the assignment of facilities to cells of a grid to minimize the transportation costs (Koopmans, Beckman, 1957). For the QAP applications, CRAFT procedure was used in Facility Layout® program. Computerized Relative Allocation of Facilities Technique, CRAFT, was formulated in 1963 to increase the efficiency of a manufacturing plant, speed up the evaluation process and to generate more alternatives to the space layout problem (Buffa, Armour, Vollmann, 1964). Facility Layout® is a program which uses CRAFT in space layout organization. The program uses improvement approach, which decreases the total cost of an initial layout by doing pair-wise switches during the optimization. Design units of unequal sizes are subdivided into standard modules. The program operates in Microsoft Office Excel® (Jensen, 2004).

AFM is an equilibrium method application and Kangaroo Physics program was used for this model’s construction. Equilibrium method is the application of Newton’s second law of motion on the design objects in the space layout to reach an intended design state. Kangaroo Physics is an add-on of a3D Modeling Program, which interactively simulates physical rules in a 3D environment and gives the user the chance to interact with the behavior during the simulation (Piker).

The designer also used intuitive approach in the process next to computerized space layout approaches. Intuitive approach uses satisficing instead of trying to find the optimum result as in the cases of the computerized space layout approaches.

There are various advantages and disadvantages of the different approaches, such as representing various architectural information of intuitive approach, practicality of AFM and alternative space layout optimizations with same given input of QAP. Intersecting forces and the absence of a resulting space layout evaluation mechanism of AFM and extensive input preparation and transfer of input of QAP can be mentioned as disadvantages of those approaches. Representations of the computerized space layout approaches should be evaluated by the designer and has to be improved for the further design process. Considering those experiences, the ways to increase the usefulness of computational space layout approaches in the professional field will be discussed.

Initially a brief review of the space layout approaches will be mentioned. Principles of QAP and AFM will be explained and similar researches about the usefulness of the computerized space layout approaches in the literature and the use of these approaches in practice will be presented. Following that the methodology of the research will be explained for three different approaches in detail. Lastly results of the

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3 by Daniel Piker
applications with these approaches will be given and the conclusions on this research and recommendations for future work will be mentioned.

2 Space Layout Approaches

Space layout approaches usually contain both representational approaches and evaluation methods. The comparison of the space layout approaches used in this research based on those representational and evaluation differences and their possible effects on the design process required a particular classification as such, not specifically mentioned in the literature.

Representation approaches are ways of abstracting the topological relations in and/or geometric features of the space layout for analysis and synthesis of space layouts (Baykan, 2010). Those approaches could be classified as graphs/wall representations and constraint-based approaches like region connection calculus and rectangle algebra (Baykan, 2010). Shape grammars are also used for describing, analyzing and synthesizing the space layouts. Next to these methods, other basic representations also exist like, grid representations of QAP model and point representations in space of AFM.

Evaluation methods are ways of analyzing the space layout based on designer’s criteria and altering it with different methods. Those methods could be classified as satisficing and optimization methods. Finding an acceptable or good enough solution to a design problem where best solutions are unknowable is called satisficing (Simon, 1981). Selection of good enough solutions doesn’t mean that the designer is satisfied with less but he has no other choice. The designer used only satisficing method during the intuitive approach in the design process. The technique of finding the best result or possibly best results of a design problem according to specified necessities is called optimization (Arvin, 2004). QAP and AFM use optimization method. However during the applications of the computerized models designer also used satisficing method for their evaluations.

A review of space layout approaches and programs developed for these approaches can be found in the article of Singh and Sharma (2006).

2.1 QAP

Koopmans and Beckman (1957) formulated the problem of locating facilities and activities in space as the QAP. QAP is formulated as the assignment of facilities to cells of a grid to minimize the transportation costs. The method was developed for the benefit of companies in terms of cost minimization literally however cost also defines the weight of relations between design units. The further use of the term could be understood as such.

Fixed cost term and interactive cost term is calculated in the QAP formulation and gives a total cost. QAP tries to find an suitable arrangement to decrease the amount of total costs. Fixed cost is dependent on the assignment of a design unit to a particular site and is independent from the interactions with other design units whereas
interactive cost term calculates material transportation flow costs and design units are interdependent (Liggett, 2000). The formulation is as below (Kay, 2009):

\[
\text{Given, } \quad M = \text{design units} \quad M \leq N = \text{sites} \quad (Kay, 2009)
\]

\[
M = \{i,j,\ldots\} \quad N = \{k,l,\ldots\}
\]

Minimize \( TC \) (Total Cost)

\[
= \sum_{i=1}^{M} \sum_{k=1}^{N} c_{ik} \cdot x_{ik} + \sum_{i=1}^{M} \sum_{k=1}^{N} \sum_{l=1}^{N} \sum_{j=1}^{M} c_{ijkl} \cdot x_{ik} \cdot x_{jl}
\]

subject to

\[
\sum_{i=1}^{M} x_{ik} = 1, \text{ for all sites } k = 1,\ldots,N
\]

\[
\sum_{k=1}^{N} x_{ik} = 1, \text{ for all design units } i = 1,\ldots,M
\]

\(x_{ik} = \begin{cases} 
1, & \text{if design unit } i \text{ is assigned to site } k, \\
0, & \text{otherwise}
\end{cases}
\]

where

\(c_{ik} = \text{fixed cost of assigning design unit } i \text{ to site } k\)

\(c_{ijkl} = \text{cost of assigning design unit } i \text{ to site } k \text{ when design unit } j \text{ is assigned to site } l\)
Let’s assume that, M number of design units will be assigned on N number of sites as in Figure 1-I. A possible assignment is shown in Figure 1-II, where design unit i was assigned to site k and design unit j was assigned to site l. The assignment of any design unit on any site has a cost, so this cost will be calculated as fixed cost term. For instance, in the formulation above xik value will be 1 according to this assignment. Then fixed cost of assigning design unit i to site k, cik will be valid and calculated in the formulation.4

Secondly the interactive cost term will be calculated between design unit i and design unit j. The values of xik and xjl will be 1. Then cost of assigning design unit i to site k when design unit j is assigned to site l, cijkl will be valid and calculated. The value cijkl is calculated by (cijfij)dij, which is the multiplication of the material

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4 Not every QAP program calculates fixed costs, like the one used in this thesis, Facility Layout®.
transportation flow cost (cost matrix, flow matrix) and distance. Material transportation cost and material transportation flow matrixes were both defined by the designer as an input before the optimization. Distance can be calculated either by taking the rectilinear distance or euclidian distance between the centroids of design units i and j as shown in Figure 1-III during the optimization. Total cost (TC) of the space layout is obtained by this method.

The illustration; shown in Figure 1, has 4 design units and 4 sites. The number of all possible assignments for this problem can be calculated by $M!$, which is $4! = 4 \times 3 \times 2 = 24$. However realistic space layout problems usually contain more than 15 design units, which makes it hard for QAP to consider all possible assignments because of vast numbers of solutions (Liggett, 2000) and extremely long computation time (Armour, Buffa, 1963).

Since QAP isn’t able to evaluate all possible assignments of realistic design problems, optimum result is harder to find. Based on this, researchers developed procedures to find the optimum solution; which are constructive and improvement procedures.

Constructive procedure places the most strongly related design unit in the center of the layout and continues until no design units left while the total cost is being minimized.

Improvement procedure makes pair-wise switches between the design units to decrease the total cost. In pair-wise switching, two design units exchange their sites and the new cost is calculated according to this new organization. A widely used algorithm of this procedure is CRAFT. CRAFT makes pair-wise switches between either adjacent design units or design units of equal sizes 5 (Armour, Buffa, 1963).

Applications of CRAFT for buildings of different functions are exemplified in Buffa, Armour and Vollmann’s article (1964). It is possible to fix design units at desired sites by the designer’s request. The maximum capacity of CRAFT program was 40 design units, when it was first formulated. To deal with larger sized problems different kinds of procedures were developed under improvement procedure, like, simulated annealing (Jojodia, Minis, Harhalakis, Proth, 1992) and genetic algorithms (Jo, Gero, 1998); however they mostly end up with suboptimal results.

QAP is applied with Traditional CRAFT method in Facility Layout® program; which operates in Microsoft Office Excel® 6 (Jensen, 2004).

2.2 Equilibrium Method

Newton’s second law of motion states that, to change the design object’s velocity and position, a force should be applied on it. Equilibrium method can be defined as the application of Newton’s second law of motion on the design objects in the space layout to reach an intended design state to satisfy various topological or geometric

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5 Design units of unequal sizes can also be switched; but separations more likely to occur between the modules of the same design unit.

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design criteria. Arvin and House (2002) states that any design criteria which are related with the position of any design object in the space layout can be translated into forces as shown in Figure 2., where a designer’s problem is translated into a dynamics problem.

![Figure 2: Translation of the designer's problem on the left to a dynamic problem on the right. Arvin, 2004.](image)

The lines on the left image represent the bounding walls of the design units, where on the right side, points represent the design unit centers, black lines represent extensions from the centers to the bounding walls and the light grey lines represent the forces to be applied to satisfy the design objectives between those design units.

Topological criteria regulate how one design unit relates to another, like adjacency, separation, orientation, etc. are applied on the center of the design units; geometric criteria regulate the design unit boundaries, area and shape, like alignment, offset, area, proportion, etc. are applied on the edges of the design units (Arvin, House, 2002).

Circular geometries are used to satisfy the topological criteria, to maintain the design units to slide over each other, without preventing each other during the displacement. However after the topological criteria are completed, Arvin and House (2002) recommends to transform the circular geometries into rectangular geometries during the implementation of geometric criteria, to evaluate the design unit’s shapes and the boundary relations with each other.

An important concept of the equilibrium method is shown below in the Figure 3.
In Figure 3, m0 and m1 represent two points. A spring connects the two points with spring constant, k01 and current spring length is l01 is the magnitude of the vector between positions x0 and x1 at the current time. Desired rest length between the design units is r01. Dashpot has a damping constant of d01.

Spring uses the f0 and f1 forces, with a magnitude proportional to l01 - r01. The direction of the force will be along the line connecting the two masses. The spring applies a force to bring the masses together or apart, when they move further or closer to each other respectively. The parallel attached dashpot damps the motion of the masses by producing forces proportional with damping constant, d01 to their relative velocity towards or away from each other, thus reducing the kinetic energy introduced by the spring forces (Arvin, House, 2002).

Equilibrium Method is applied with AFM. AFM was constructed in Kangaroo Physics add-on (Mulders, 2012) with necessary components to organize separate masses, in this case design units, by physical forces according to adjacency relations. Kangaroo Physics add-on, which interactively simulates physical rules in a 3D environment and gives the user the chance to interact with the behavior during the simulation (Piker). The program operates in Grasshopper®.

### 2.3 Use of Computerized Space Layout Approaches in Practice

Performance of computerized space layout programs was an interest of the space layout researchers. After the presentation of QAP program CRAFT in 1963 by Armour and Buffa, Scriabin and Vergin (1975) published an experiment based on the comparison of humans and computers for the efficient solution of the problem of space layout. This publication initiated discussions (Buffa, 1976) (Scriabin, Vergin, 1976) and differently structured experiments were published to analyze the performance of the programs, which concluded in favor of humans or computers as in

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The program can be found in Mulders, 2012 (I).

Grasshopper® is the ‘explicit history’ plug-in of Rhinoceros® 3D Modeling Program.

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Coleman’s (1977), Lewis and Block’s (1980) and Trybus and Hopkins’s (1980) works.

Baykan (1995) presents an evaluation of QAP by interviewing two designers in different companies. Both designers use the program in the block plan design phase, by input preparations and optimizing multiple initial configurations. Despite advantages like dealing with complexity and increasing the confidence of the designer on the layout, the software used have difficulties like extensive input preparation and transfer of output to other sketching programs.

Another research by Canen and Williamson (1998) seeks the use of computerized space layout approaches by the companies and their contribution in the competitive purposes. The research showed that academic research is not really known by companies and doesn’t reflect on their practice and the companies are not interested in academic research either and deal with the problem by their own methods.

Lobos and Donath (2010) state that 50 years of research shows that none of the computational solution methods are practically used or accepted by the architects and relate this with both space layout researchers and architects the lack of interest in each other’s fields in approaching the problem.

3 Methodology

The process was initiated by the definition of the design program of a creative facility, composed of 69 design units. 56 of 69 design units are together in a core, composed of four functional zones, and additional 13 design units are separately distributed on the site.

After defining the qualities of the design units and their possible desired relations, the space layout problem was complex enough to solve manually due to vast number of design units. Therefore performance of three different approaches for the solution of this problem was researched.

The operations were done and evaluated by one designer, who is the author of this research. Three space layouts were obtained from the three different approaches and necessary inputs for the evaluation processes, the evaluation processes and the resulting space layouts were analyzed. The space layouts were analyzed based on both the satisfaction of the given input and what they represent.

3.1 Analysis with AFM

Design goal of AFM research is to achieve a space layout, which produce a configuration of the design units based on desired adjacencies. For AFM applications the requirements are; list of design units, sizes of design units and the related design units or adjacency relation inputs. 58 adjacency relation inputs were prepared intuitively between 69 design units of unequal sizes including identical design units for this research. A lower limit was not defined in the beginning, but almost 50 out of 58 adjacency relations was expected to be satisfied in the resulting space layout.
Various intuitive reasoning between the design units was expressed in the same way as an ‘adjacency relation’. The reasoning is based on conditions like, having identical function, belonging to same functional zone, being functionally complementary, being visually related, having service requirements (Demir, 2014). Only the related design units have to be mentioned as an input, so the number of input depends on the designer’s objectives. AFM also doesn’t require quantity of adjacency relation. These two features of AFM speed up the input preparation phase and prevent additional complexity for the designer because a relation can be defined whenever it is thought as important.

The space layout initially consists of randomly distributed design units in circular geometries with names written on without any space layout boundary. The configuration only depends on the order of design units in the list, so it is not possible to initiate the optimization process with an initial space layout configuration.

During the optimization related design unit names were transferred into strings and theirs centroids were connected to a component, which attracted them to each other, therefore all of the design units displaced according to 58 adjacency relation inputs with initial adjustments of AFM. After the state of equilibrium a space layout was obtained. Designer evaluated the layout visually by comparing some of the relations in the layout with the given input and saw that most of the relations were not satisfied and adjusted features like damping or stiffness in the spring component or strength of the power law force of AFM. First space layout was obtained with modified adjustments of AFM after multiple trials with the satisfaction of the majority of the relations, which is 53 out of 58 relations as shown in Figure 4.
Fig. 4. Relation satisfactions of space layout of AFM. P indicates the parent design unit. The little colorful arrows show the attraction of identical design units to the parent design unit. Big black arrows indicate satisfied relations. Big red arrows indicate not satisfied relations. Drawn by the author.
3.2 Analysis with Intuitive Approach

Design goal of intuitive approach research, is to develop the space layout according to various criteria. The analysis process is more designer oriented and unique and without any dependence on a computerized space layout approach. For intuitive approach, the designer identifies which kinds of inputs are required. In this work input about which design units are public or private, which design unit belongs to which zone, which design units should be secluded; height, sound isolation, light / dark design units were prepared intuitively (Demir, 2014). Inputs on the site and environmental conditions, like site elevations, sun path, wind directions, were also gathered from external sources (Demir, 2014). Neither of those inputs were used in the other models. During satisficing process the designer applied those input one by one on the layout obtained from AFM applications. Those steps developed the initial space layout and formed a new one as shown in Figure 5.
Fig. 5. Space layout of intuitive approach. Drawn by the author.

3.3 Analysis with QAP

Design goals of QAP research is to observe the optimization performance of the model by initiating the process with various space layouts including a random space layout generated by Facility Layout® and the space layout of the intuitive approach. Those space layouts include a random layout, a random layout with 4 design units fixed on the desired zones, a random layout with 10 units fixed on the desired zones, space layout of intuitive approach and space layout of intuitive approach with identical units adjacently placed. The reason of adding space layouts with fixed design units in the research is to analyze the relations both between the design units and between the design units and the site during the optimization process.

For QAP applications the requirements are; list of design units, sizes of the design units, flow matrix of the design units, material handling cost matrix of the design units, and the size of the proposed space layout in length and width.

For the assignment of flow matrix inputs between the design units, sensitivity analyses were done using different flow input sets (Demir, 2014). After the sensitivity analysis, selected input values were assigned between the design units depending on the strength of their relationship. 1431 flow inputs were given to the flow matrix for 54 design units in the core of the design, of unequal sizes, including identical design units (54*(54-1)/2 = 1431). These inputs were coherent with the adjacency relation inputs from the previous AFM applications. Material handling cost matrix inputs were taken as 1 for each relation; to avoid additional complexity when multiplied with the flow matrix (Demir, 2014).

Interdepartmental flow is mostly used for materials, but in buildings of different functions, it can be used for other criteria like people flow, etc. (Buffa, Armour, Vollmann, 1964). As in the previous processes, different reasonings like being in the same zone, functionally complementary, people and material flow and so forth were expressed in the same way. If the relation was strong, then the highest flow input was given.

Fixed cost inputs are not requested nor calculated by the program. But the designer manually calculated the results of the fixed cost analysis to analyze the relation of the design units with the site. Initially three zones were identified on project site related with main transportation axis and landscape. Modular layout of the Facility Layout® program was translated into the project site. A fixed cost was given for each design unit for each one of the three zones. Fixed cost inputs were given based on the same intuitive reasoning used in the intuitive approach. Lower costs were given to the design units to be placed in a desired zone.

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10 After the use of AFM in the design process, intuitive approach was used to organize the space layout of the design. During the intuitive approach, identical units were placed separately to increase interaction in the core. However identical design units were placed adjacently in the layout mentioned.
A random space layout of Facility Layout® initially consists of sequentially allocated design units in modular geometries with numbers representing the names written on and with a cost. The designer can also initiate the optimization with an initial space layout configuration.

Total costs of the layouts before and after the optimizations were noted down. Fixed costs and relation satisfactions of the optimized layouts; according to given flow matrices were calculated manually. The layouts were redrafted from grids to bounded spaces, where design units exist, and their functionality was analyzed in terms of their functionality. One of the optimizations with the least cost was selected as the third space layout as shown in Figure 6.

Facility Layout® doesn’t request and calculate the fixed costs, but a manual calculation was done by the designer to analyze the relation of the design units with the site.
4 Results

All space layout approaches were useful in the design process to a degree. AFM was basic and practical in preparation of inputs and transfer of the outputs. QAP led to design variations prevents the conditioning on the first result found and allows the designer to initiate the optimization process with a desired space layout configuration. Intuitive approach represents the architectural qualities of the design best.

The main disadvantages of the three approaches can be explained as follows. In AFM the intersecting forces, such as spring and power law, decrease each other’s efficiency and led to high numbers of unsatisfied relations in the resulting space layout. In this case the designer should adjust the model parameters and do multiple trials to reach to a better result. The model is also not capable of generating an alternative space layout to the given relations in the given order of the design units in Microsoft Office Excel® file with the same adjustments. So the designer may be conditioned on the resulting space layout. Another important finding is that AFM is sensitive to; design unit scales, initial configurations, sizes and number of design units. The designer should be aware that changes in those criteria could alter the resulting space layout.

During the intuitive approach, the designer developed the space layout gradually based on satisficing without seeking for the optimum result. Depending on the designer, generating an alternative space layout in the same detail of representation may be more compelling than the computational space layout approaches.

In QAP mainly the preparation of input is complex and time consuming because the flow matrix requires $n^2(n-1)/2$ flow inputs, which gradually differentiate depending on the strength of the relation between the design units and QAP is sensitive to different gradual flow inputs. The random selection of switching pairs may create a narrow solution space, and end up with weak solutions. Multiple trials are necessary in QAP to have an idea about the limits of the solution space. QAP may generate space layouts with lesser costs than the space layout of the intuitive approach as a result of higher number of switches during the optimizations and with irregular and disconnected design unit boundary shapes at the end as a disadvantage. Another issue of QAP is the transfer of output to other drafting programs.

None of the methods contain a practical method to understand the satisfaction of desired relations, except the space layout cost in QAP. However the cost is not a strict indicator of satisfaction of desired relations because there may be several reasons of a low cost like more switches and irregular design unit shapes or an initial representational layout with low cost or different flow input sets. So the cost evaluation should be supported with additional evaluation methods.

Design criteria are better to be quantifiable during the formulation of the problem so the results can be understood accordingly and well judged (Kalay, 2004). To understand the performance of the program, the highest flow inputs were checked one
by one by looking at the relations of the design units on the resulting space layouts. A
color was given to each relation according to the final positions of the design units in
the space layout as illustrated on the left of Figure 7. However this method is more
difficult in QAP than AFM, as the number of input to check increases. Space layouts
with low costs have the highest relation satisfactions and layouts with high costs have
the least relation satisfactions. Relation satisfactions color schema on the right of
Figure 7 shows that, relations with blue color turn to red and claret red colors after the
optimizations.

The relations of the design units with the site were checked by calculating the fixed
costs during QAP applications manually. It was seen that as the number of the fixed
design units increased, fixed cost of the optimized space layout decreased. This is
related with the designer’s same intuitive reasoning on identifying the flow inputs and
fixed cost inputs. Site allocations were mostly taken into consideration during
intuitive approach, but not in the applications of AFM.

Resulting space layouts of all approaches have different representations with
varying levels of details as shown in Figure 8. The designer realized that the space
layout representations of AFM and QAP don’t contain majority of the necessary
architectural information, but only carry the information on the given input based on
the size of the design units and the adjacency relations. Even if design unit boundary
shapes, space layout boundaries and circulations are represented in the space layouts,
it is not known if these representations are valid for the design or will be used in the
further design process. So the designer should decide if they are coherent with the
design criteria or not and design them from the very beginning for the further
processes if necessary. For the further design process additional analysis could be
done to detail the space layout representations.

Brief notes of the author on the improvement of the models are: In AFM; additions
of an evaluation mechanism\(^\text{12}\) to understand the satisfaction of desired relations and a
component\(^\text{13}\) to change the order of the design units in Microsoft Office Excel® file,
therefore their initial configurations to end up with space layout alternatives. The
modification of the model structure according to gradual adjacency relation inputs is
also possible but it may also increase the complexity of this basic model and add
difficulties like input preparation in QAP. In QAP, additions of fixed cost calculations
to the program to strengthen the relation of the space layout with the site and export
options to drafting programs would be useful.

\(^{12}\) A component could be added in the model to relate the adjacency relations to the distances
between the design units in their final positions.

\(^{13}\) The initial configuration of the space layout in AFM depends on the order of design units in
Microsoft Office Excel®. A number slider can be connected to the random initial distribution
component and as it changes, the initial random placement can change quickly and give
multiple results.
Fig. 7. Relation satisfactions of space layouts of QAP were checked visually by the designer. Only the strongest relations were rated according to their satisfaction. Colors were given according to the final positions of the design units in the space layout on the left. Satisfied: Claret red, Partly Satisfied: Red, Unsatisfied: Yellow, Not related at all: Blue. Relation satisfactions color schema is on the right. Layouts from left to right:
1-a random layout, 2-optimization of 1, 3- a random layout with 4 design units fixed on the desired zones, 4-optimization of 3, 5- a random layout with 10 units fixed on the desired zones, 6-optimization of 5, 7-space layout of intuitive approach, 8-optimization of 7, 9-space layout of intuitive approach with identical units adjacently placed, 10-optimization of 9
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From 1 to 10; relation satisfactions increase with the increase of designer control on the initial space layout. Drawn by the author.
Fig. 8. There space layouts by AFM, Intuitive Approach and QAP from left to right. Entrance was highlighted with red in all layouts. Drawn by the author.

5 Conclusion and Future Work

The usefulness of computerized space layout programs are researched by using two computerized space layout approaches, AFM and QAP and an intuitive approach by one designer, in a design process of an actual problem of space layout of more than 50 design units of unequal sizes. In those three processes, the designer observes the input preparations, optimization and satisficing processes and resulting space layouts. The evaluations of the space layouts are based on both the satisfaction of the given input of desired relations and what the space layouts represented. Three space layouts were generated as illustrated in Figure 8. The research showed that each approach uses different evaluation methods and representation approaches, which gave an idea to understand the potentials and disadvantages of the computerized space layout approaches and their convenience for various design states in the problem of space layout.

The intuitive approach develops the space layout gradually based on a search for satisficing solutions, while the computerized space layout approaches use optimization method and try to reach the best result. To take maximum advantage of the computerized approaches, the designer should modify their structure by multiple trials, adjusting and understanding the effects of the parameters. More alternatives the programs generate, less conditioning on the results. This is the biggest advantage of the computerized models over the intuitive approach. In this research, only QAP could generate alternative solutions with the given input and initial adjustments, nevertheless it is also possible to modify AFM and benefit from its potential.

The space layouts generated by the computerized models helped the designer in the solution of a complex problem. The results were reliable and helpful, especially after the familiarity of the designer with the model. So the discussion on the efficient solution of the problem by human or computer is not a question of the designer after this research. However the discussion on the usefulness of the computerized space layouts in the professional field still exists and the ways to improve the computerized space layout approaches should be the matter of discussion. The author agrees with the two recommendations of Lobos and Donath (2010) for architects and space layout researchers, where space layout researchers should try to reach architects by understanding their approaches about good and efficient architecture and reflect on that and architects should try to understand how space layout researchers approach to the problem of space layout. Computational approaches should be integrated in educational programs and merge with the traditional space layout methods. Architects representing this new trend may create boutique approaches for their own design processes, rather than expecting the space layout researchers to approach to their problems.
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Note
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Development of parklets by using parametric modeling

Henrique Benedetto, Fabrício A. Kipper, Vinícius Marques, Underléa M. Bruscato

Federal University of Rio Grande do Sul
henrique.benedetto@ufrgs.br, fakipper@gmail.com, vini3dz@gmail.com, underlea.bruscato@ufrgs.br

Abstract. The lack of urban planning has made the recreation areas increasingly smaller in the cities. Parks and squares gradually gave way to streets and avenues to try to accommodate the growing number of cars and motorcycles. An alternative that tries to balance recreation areas and urban roads was found in the city of San Francisco (USA). Parklets are temporary extensions of urban sidewalks that occupy a few parking spaces. This article aims to demonstrate the potential of parametric modeling in the development of parklets. Thus, anthropometric studies, amount of parking spaces and types of benches were used as input parameters. Rhinoceros and grasshopper programs were used for modeling, while 3D Studio Max was used for rendering. With this study it was possible to verify that when the project is parameterized the processes of creation and modification became faster, reducing design and implementation time.

Keywords: Grasshopper algorithm editor, parametric model, parklets.

1 Introduction

The Industrial Revolution was a breakthrough for society because the production form went from a handcrafted scale to an industrial scale. Thus, the demand for jobs in factories caused a lot of migration of peasants to the cities.

The pace of growth of most cities could not keep up with all the needs that this new reality presented. The streets, which were former exclusive areas for chariot circulation, started having the circulation of cars. In favor of urban mobility, public leisure spaces were being gradually replaced by streets and avenues. [1]

However, the solution for urban mobility is not associated with the increase in the number of roads, but with the way people move. Stimulating the displacement by collective or non-motorized means of transport (bicycle, for example) is indicated in the guidelines of the National Policy on Urban Mobility (PNMU) established by Law No. 12.587/2012. [2]

Initiatives that aim to rethink the space of circulation have already been taken in some cities. In London, there are signs that indicate the walking distance from the main sights. In Philadelphia and New York, street space is being turned into multipurpose spaces: bike paths, sidewalks and squares. [3]
The creation of squares in urban centers is a problem because there is a lack of large public spaces in central areas of big cities. To try to change this situation, parklets, or mini-parks, originated in the city of San Francisco (USA) [3].

Parklets consist of the extension of temporary public footpath (sidewalk) occupying some areas which, until then, were dedicated exclusively to parking vehicles, through the implementation of a platform equipped with benches, tables and chairs, roofs, exercise equipment, or other street furniture having recreation function [4]. The great benefit in implementing parklets is increased awareness and coexistence between people and transport vehicles, both conventional (cars and motorcycles) and alternative (bike, skateboard). Parklets, because of their ephemeral construction features, give cities a significant aesthetic movement, regarding the perspectives of the cities, which are full of static buildings in the urban scenario. Parklets are dynamic, constantly changing the visual of the city and in a healthy way, the population. The parametric design concept applied to parklets contributes to the excellence in a contemporary character design, taking into consideration the essence of project design and manufacturing.

This project aims to meet the current demand for public spaces in the form of parklets and considers anthropometric dimensions for the design of a set of street furniture items, chairs and loungers, besides the development of a roof.

Using the paradigm of parametric design, this furniture can be manipulated to generate alternatives that meet the needs of different available public spaces. Thus, the purpose of this study is to investigate the potential of parametric modeling for the development of parklets.

2 Methodology

To verify the potential use of parametric modeling we opted for the development of parklets whose main function is to provide the user with a rest area. For this purpose, a chair composition and a covered area were created. That definition was based on the design time (3 months) and on the size of the available staff. This research was carried out in a course of the Post-graduate Program of Design at the Federal University of Rio Grande do Sul in 2014 with the objective to verify the development process of parklets by using parametric digital modeling.

The research was organized in two phases: exploratory literature review and the virtual and physical simulation of parklet prototypes. In the exploratory phase, the objective was to verify which design requirements should be considered in developing a parklet. These requirements were used as input parameters in the algorithm to be created in the Grasshopper program.

In Brazil, the municipality is responsible for the creation of regulations for operating parklets. During the research, it was found that few Brazilian cities have operating regulations. The city of São Paulo, for example, has already created a handbook with regulations for those who want to implement a parklet [5].

These regulations are divided into six categories, namely:
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**types of parking spots** - if it is an oblique or parallel parking space;

**distance from the corner** - parklets cannot be installed less than 15 meters from the edge of the street cross section;

**limitations** - parklets cannot obstruct curb cuts, bus stops, taxi stands, pedestrian crossings and handicapped parking spaces;

**accessibility** – they must meet the technical standards established in Art. 5 of Decree no. 55.045/14;

**drainage** - the installations should not occur on manhole covers or in areas with occurrence of floods;

**sloping streets** - parklets can only be installed on roads with up to 8.33% of longitudinal slope.

As input criteria to create the algorithm the type of parking space was selected (Figure 1) which defines the maximum space of occupation in parallel parking spaces positions 2.20 m wide starting from the alignment of the street curb and 10 m long. Regarding perpendicular or oblique parking spaces, the alignment should be 4.40 m wide and 5 m long.

![Fig. 1. Graphic representation of the maximum space for the implementation of parklets in the city of São Paulo. [5]](image)

Accessibility criteria and slope of the streets were not used in this study because they would increase the control variables and, as a result, the complexity of the algorithm to be created. However, this implementation is recommended for future studies. As for the other criteria presented (distance from the corner and drainage), they are not considered input parameters that influence the project design.

Other data used in this project are the dimensions of benches and ceiling. For these data, we used the results of the master’s thesis by Ana Claudia Vettoretto entitled “Benches to read and talk: Design parameters for generative design system” [6].

In her thesis, Vettoretto surveys the several postures users of park benches adopt while reading and chatting. Taking this information into consideration, the author checked the postural tendencies adopted while performing those activities and developed a guideline for the design of these types of benches.

To verify the input parameters 9 bench profiles were selected (Fig. 2), where the user can keep their legs extended or flexed.
Fig. 2. Profiles selected as input parameters in the algorithm

Because this project is based on digital manufacturing, the wood sheet thickness and the distance between sheets will be considered, as this information will be essential for the generation of parts for laser cutting.

For the second phase of this study, which consists of virtual simulation, the program Rhinoceros was used to visualize the object generated from the algorithm developed in the Grasshopper program. Since the focus of this research is to verify the potential for using parametric modeling when designing parklets, a full-scale prototype was not developed. Instead, a physical scale prototype was developed and a 3D Cliever printer (type Black Edition) was used.

3 Results and Discussion

For the generation of the 3D models the program Rhinoceros (Rhino) was used with plug-in Grasshopper (GH) by drawing all geometric elements of the base curve of the structure to be projected. Although this method allowed a total mastery of design variables such as height, width and length of the roof, height and depth of the bench, whether there are curves or not in the layout of the bench, wave effect on the height and top of the bench, it provided a very poor result and did not allow an ergonomically proper design. Figure 3 shows an example of the first result obtained.
Since the first results it was easy to identify GH potential to assist in the development of complex models, test several concepts of product design, try new approaches and allow the designer to develop a relational and adaptive design. [7].

In search of a better definition to the model in terms of shape, visual design and ergonomics, it was decided that the project would start with a set of previously defined curves, instead of generating the curves in the GH. A set of projects of benches ergonomically designed by Vettoretti [6] was then taken as a basis and it was added a more organic and fluid form, based on the concept of the “Great Wave off the coast of Kanagawa” painted by Hokusai, which served as inspiration, for example, for the construction of the Yokohama International Marine Terminal in Japan by FOA (Foreign Office Architects) [8] as shown in figure 4 and 5.
Fig. 5. Reference curves developed

The definition of the curves increases the degree of project control and makes it possible to generate different models of parklets with the addition of new geometries. When a new curve is inserted, it is projected and added to the model base set, which regenerates and accommodates to the new geometry. One of the positive aspects in the parametric adjustment of curves is the transition control between them, because this is one of the ways to ensure that the predicted ergonomic aspects will not change (Fig. 6). Therefore, when this control is used it is possible to ensure a smoother transition between curves.

Fig. 6. Reference curves developed and ergonomic aspects
The algorithm developed in the GH consists of some building block models. Figure 7 presents the parameter block, both of the sheet to be considered for the production and of the curves that will be used as a basis for building the model.

![Fig. 7. Model parameters](image)

Once the curves are defined, whether the same or different, and the dimensions of the project, the project itself was developed. It consisted of 4 geometry modules, which was defined by the fixed number of curves that would be used. The correct curve positioning was reached with the fractions of codes shown in Figure 8a.

![Fig. 8. Positioning modules of reference curves](image)

Following the method of successive copies of these curves it was obtained the skeleton of the model structure, as shown in figure 9a, the code and in 9b the structure.
We decided to generate a large number of intermediate curves to ensure a smooth transition between the curves, and, thus, ensure that there was no distortion of the ergonomic baseline study.

To ensure that the same orientation of the curves is achieved when generating the lofting of the model, the guide curves were generated in a controlled process and not at random by the Grasshopper function. This attention was necessary in order to eliminate fouling in the resulting model, generated by differences between the geometries of curves and misalignments and their number of constructing points. Figure 10 shows the code and the result of this operation.
Fig. 10. Lofting control algorithm and virtual model

With the generated lofting the structure for the slicing and generation of the final model to be manufactured is obtained. Considering the initial parameters of wooden sheet thickness and distance between sheets the sections of the model were created.

Once the final model is a set of sheets separated from each other, a support was developed to be placed between the sheets, without changing the visual design of the model. This support is said to be universal since its dimensions allow its use with any geometry of curve chosen to set up the Parklet model.

Finally, the sheets and brackets are united in one element, thus concluding the desired Parklet model.

Fig. 11. Algorithm of sheet bonding

One of the advantages of using a tool such as Rhino/Grasshopper is the possibility of generating the cross-sectional profile for a nesting algorithm, and, thus, materialize the constructive elements of the model.

In this study, physical prototypes of one of the parklet variations developed were printed in 3D printers, as illustrated in figure 12.
Fig. 12. Prototype made in a 3D printer.

With the virtual model generated by Rhino / Grasshopper the file was exported to 3D Studio Max in order to create the final rendering of the project that can be seen in Figure 13.

Fig. 13. Final model of parklet
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4 Conclusion

When a project is parameterized there is design time optimization, which can be seen during the phase of generating alternatives and in the manufacturing process, which makes its use a major competitive differential. The use of parametric modeling was efficient in developing parklets, because for each area of a city there can be different design requirements (inputs). The study also showed that in the project scope phase it is necessary to define the variables involved and their relationships to create the parametric code in Grasshopper. However, if there is a need to include new parameter during the project this can be done without affecting what has already been performed.

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Making sense of those batteries and wires
Parametric design between emergence and autonomy

Sherif M. Abdelmohsen and Passaint M. Massoud
The American University in Cairo
{sherifmorad, drpassaint}@aucegypt.edu

Abstract. This paper reports on the process and outcomes of a digital design studio that integrates parametric design and generative systems in architectural and urban design projects. It explores the interrelationship between the emergence of innovative formal representations using parametric design systems on the one hand, and design autonomy; more specifically the conscious process of generating and developing an architectural concept, on the other. Groups of undergraduate students working on an architectural project are asked to identify a specific conceptual parti that addresses an aspect of architectural quality, define strategies that satisfy those aspects, and computational methodologies to implement those strategies, such as rule-based systems, self-organization systems, and genetic algorithms. The paper describes the educational approach and studio outcomes, discusses implications for CAAD education and curricula, and addresses issues to be considered for parametric and generative software development.

Keywords: Parametric modeling, generative design, emergence, autonomy, design exploration, CAAD curriculum.

1 Introduction

The adoption of parametric modeling in CAAD education is becoming increasingly prevalent. With parametric modeling software tools emerging, comes the low-hanging fruit of intuitive manipulation of parametric relations, and capture and evaluation of design information and geometry. Such capabilities have mostly aligned with researchers’ goals in transforming traditional design studio from focusing on representational aspects of design into an information-centric process that embraces conceptual thinking and intuitive design exploration [1-2].

Young graduates are now carrying significant technological innovation into practice that moves beyond graphical representation into technical aspects of building performance and constructability [3-4]. One of the challenges however in implementing such transformation at the undergraduate level in CAAD education involves the students falling into the trap of tool thinking rather than comprehensive ways of thinking that extend to incorporate design, process and production [5-7].
This paper addresses the following questions: Does the ability to computationally visualize complex morphological representations guarantee an in-depth understanding of the essence of architectural ideation and concept generation? In CAAD education, especially that involves concepts of parametric design and digital morphogenesis, does a dichotomy exist between the emergence of innovative formal representations on the one hand and the conscious process of generating and developing an architectural concept on the other? If so, is such a dichotomy reconcilable, and how?

More rigorous foundations for CAAD education have long been called for in academia, where the principal issue is not of mere technology, but rather one of architecture and design principles [8]. In this context, how can design studio then foster advanced digital design thinking methods without compromising conscious design decision making? Can designers implement parametric and algorithmic design methods while still maintaining “control” of their emergent designs? In order to attempt at responding to these inquiries, this research explores the process of form generation and concept development, between emergence and design exploration, in the context of a digital design studio.

One of the major challenges in “digital” design studios is the gap that exists between presenting the fundamentals of architectural design using digital media on the one hand, and providing the digital toolset, skills and techniques necessary for implementing those fundamentals on the other [9]. Some studies highlight the problems arising from this gap, where students fail to fully capitalize on the digital skills acquired during a given semester in actual design exploration till very late in the process, often not really coming to fruition and full maturity until subsequent semesters, therefore presenting challenges in terms of knowledge acquisition and application [10]. More recently, parametric and generative design systems have been viewed as much more valuable than mere “tools”, but as complementary processes to design conceptualization, thinking, development and production in architecture [11], where both formal and conceptual approaches are assumed to develop concurrently into emergent designs and innovations.

This paper goes further into exploring closely the process of cultivating intangible concepts, understandings and meanings into tangible formal representations in parametric and generative design tools. Groups of students working on designing an exposition center are asked to explicitly identify a specific conceptual parti that relates to an aspect of architectural quality (such as expressing motion, flow, growth, coarseness, abundance, complexity, etc.). They are required to define strategies that satisfy those aspects, and computational methodologies to implement those strategies (such as rule-based systems, self-organization systems, genetic algorithms, etc.). Then they are required to implement the basic procedures in Rhino’s graphical algorithm editor; Grasshopper, to achieve those methodologies and strategies.

The following sections explicate the theoretical framework that drives this research, followed by a brief description of an architectural design studio focusing on parametric and generative design. The paper discusses the main observations pertaining to design exploration, emergence and autonomy, and presents a detailed observation and discussion for two of the student projects. Finally, the affordances and limitations of parametric and generative systems as exploratory tools are discussed, with specific focus on their role in CAAD education, and on future opportunities for software tool development.
2 Between Emergence and Autonomy

Traditionally, the shift of CAAD from solely aiding drafting, increasing efficiency and representing geometry to generative and parametric methods that embody “the representation and use of knowledge to support or carry the synthesis of designs” [12] has widely contributed to expanding possibilities of design exploration, both formally and conceptually. Visual parametric modeling tools and graphical algorithm editors such as Grasshopper have added another dimension, whereby conceptual and visual explorations precede – to some extent – intense computational and programming proficiency, therefore assuming wider acceptance in the architectural design community.

According to Neil Leach, the logic of a design is more at stake in generative design systems rather than the designed artifact or product itself [13]. This notion is further augmented by Dino, where generative systems are said to encode the making of artifacts or procedures in the design process through higher-level specifications, where form follows formation, therefore allowing for an expanded design search and exploration space [14].

An important caveat here is what the nature of generative and parametric systems implies in terms of emergence and autonomy. Within the dynamic mechanism of assigning rules, constraints, parameters, and generative procedures, an implicit process takes place that addresses this presumed dichotomy. On one hand, designers experience much more than conventional problem solving procedures, but are rather granted diverse routes of inquiry and probing of the design problem and solution possibilities. In a more complex and richer problem and solution space, they produce and are challenged with consequences of their limitless and unforeseen solutions in a way that is very different from their original intent, planning and design strategy.

On the other hand, the autonomy of the generative system and that of the designer are both questioned. According to Peter Eisenman, autonomy should be given to the architectural object itself or more precisely its becoming, rather than its discipline or the designer involved in its becoming [15]. Watanabe argues that autonomy (which he coins „autonomy of process”) is more of a way for unraveling novel architectural solutions without being bound by the mind [16]. Dino describes the notion of autonomy – specifically in relation to the use of generative design systems in architecture – as one that exhibits a certain level of system autonomy besides the autonomy of the designer [14]. In this context, the system does not fully supersede the human designer, but some design tasks and intelligence are passed on from the designer – or more accurately externalized and programmed – into the system. It is this delegation of activities that steers the inherent relation between the conscious process of developing an architectural concept and the emergence of innovative formal representations.

The consequences of this recent perspective on autonomy of process are twofold: (1) it shows how objective processes (related to scientific methods and systematic procedures, relations and rules) and subjective processes (related to best judgment and domain-specific knowledge of designers) can be explained, and (2) it suggests the level by which architects and designers can or cannot maintain control over their
designs using generative and parametric design systems, and more significantly the implied design intent.

In an educational setting, and specifically CAAD education, this perspective is significantly relevant, as the conscious act of designing and maintaining control of design actions based on domain-specific knowledge need to guide or tame the often irrational and groundless nature of emergent solutions resulting from novice paths of exploration with parametric and generative design systems. The paper introduces in the next sections the process and outcomes of an architectural design studio that implements parametric and generative design methods.

3 Design Studio Outline and Process

This architectural design studio was one of the required studios of the undergraduate program at the Department of Construction and Architectural Engineering at the American University in Cairo (AUC), Cairo, Egypt. 18 students were enrolled in this studio, under the supervision of two instructors and one teaching assistant. The studio ran once a week for 14 weeks during the period from September to December 2014. The aim of this studio was to explore the full potential of computation, parametric modeling, algorithms and generative systems in architectural design. Students were free to explore and build on an extensible palette of parametric modeling, scripting, and analysis tools during their experimentation with form generation, evaluation and optimization methods, in order to investigate the potentials of digital design beyond preconceived notions and crossing conventional boundaries of form generation.

The project that the students worked on was an exposition center in the heart of the city of Cairo. Its components consisted of a hotel (500 rooms), an office building tower (20 stories with a multi-storey area of 10000-17000 m2), a conference center, including 3 main halls to accommodate 800-1000 persons each and 10 small halls to accommodate 300 persons, a shopping center including a mega store and 120 small shopping stores, and an exhibition area.

The studio was mainly divided into two parts: (1) group work and master plan, and (2) individual work and design development. In part (1), the main focus was on the relation between architectural function, structure and material properties, in discovering alternate methods of form generation. The students, divided into four groups, were evaluated based on their development of 3D models of the exposition center using parametric and generative design tools, in addition to addressing site conditions and constraints, and satisfying the identified performance criteria. In this stage, the students worked to develop a masterplan collectively, focusing on utilizing parametric design methods at the urban design level. Each group was advised to formulate a conceptual idea pertaining to an aspect of architectural quality, such as expressing motion, flow, growth, coarseness, abundance, complexity, and so on. The goal was to guide the students consciously through a conceptual rather than a purely formalistic approach to achieve their designs. They were advised to carry on these ideas throughout their individual work as well.
In addition, each group conducted research on generative and parametric design strategies, and was required to define strategies for their group projects that satisfied the formulated conceptual structures. They were then asked to develop computational methodologies to implement those strategies, such as rule-based systems, self-organization systems, genetic algorithms, computational geometry, and so on, based on their specific approaches. Finally the students were required to implement the basic procedures in Grasshopper to achieve those methodologies and strategies. The goal was to let the students utilize parametric design skills and techniques early in the process, especially alongside the concept generation phase.

In part (2), the students had to use parametric and generative design techniques to reinterpret their initial ideas and approaches into a more comprehensive building design exercise. The students worked individually in order to realize their individual components, and were encouraged to reflect on their group work back and forth. They were encouraged to develop models involving evaluation methods and using simulation and analysis tools regarding a topic of their choice. The final outcome of this stage included 3D models and developed plans, sections and elevations for the individual buildings, with considerable attention to the impact of this development on the group work and masterplan components.

4 General Observations

Students in this design studio were all previously exposed to basic parametric modeling concepts and skills in computational design courses throughout the CAAD curriculum, and have had some experience with using tools such as Autodesk Revit, Rhino and Grasshopper. Despite this prior experience, integrating these concepts and skills in the design studio was a different challenge, especially that this studio demanded a highly technical and early implementation of computational concepts. In addition, the implementation of these concepts was required at different scales and levels of detail, including the urban design level as well as the architectural design and detailing level.

Four groups of students developed the required master plans and further worked on their individual building components, using four main concepts: (1) responsiveness, (2) expression of time, (3) flow-ability, and (4) magnetism. The groups varied in their approaches and in how the emergent formal approaches guided their design process.

4.1 Project 1: Responsiveness

Group 1 designed their project as an exposition center that responds to multiple factors in the surrounding environment, including contextual, environmental and cultural constraints. Their concept was based on swarm intelligence systems that work with multiple objectives, and sense and respond to exterior parameters in the surrounding context, such as wind, solar radiation, noise levels and site landmarks. The group assigned three rules for their system logic: alignment, cohesion and separation. The ratio between those variables achieves an infinite number of solutions. Each of the building forms was generated through a process whereby different values were
assigned to those rules based on the logic and requirements of each building type (Fig. 1). The group used multiple software tools and plug-ins in their form generation and analysis process, including Rhino and Grasshopper for the parametric modeling component, Processing for running the swarm intelligence logic, Millipede for structural analysis, Autodesk Ecotect for environmental analysis, Autodesk Revit for documentation, and 3DS Max/Vray for visualization and rendering.

![Fig. 1. Master plan logic using swarm intelligence to express responsiveness (Group 1)](image)

4.2 Project 2: Expression of Time

Group 2 looked at time as a variable and divided their theme into three main factors: quality of spaces, spatial experience, and playing with light. They were inspired by the dynamic and seasonal features of change in nature such as the generative formation of snowflakes, flowers blossoming during spring, crystallization, leaf life cycle, and fruition. They used the meta-ball concept which is based on cell divisions using attraction and repelling fields based on change in time (Fig. 2).
4.3 Project 3: Flow-ability

Group 3 devised the concept of flow-ability, which they defined as an inspiration for form generation from both nature and human behavior. The main conceptual basis and source of form generation was derived from wind flow as well as the flow of people in the project site (Fig. 3). The group aimed at designing the pedestrian network within the site in such a way that follows wind direction. They first generated preliminary forms then conducted wind flow studies using Autodesk Vasari in order to produce an adjusted masterplan. The building components in the masterplan were explicitly shaped such that they respect the existing wind patterns based on the wind flow studies. This was consciously formalized by the students in order to maximize desired wind conditions for their designed buildings and provide enhanced wind flow at both the urban design level among the group of buildings and their interconnected spaces, as well as the three-dimensional level of each of the buildings, where each of the individual designs was fine tuned to achieve improved flow-ability. This was a back and forth exercise in Autodesk Revit and Vasari.
Fig. 3. Master plan using wind flow studies in Revit/Vasari to express flow-ability (Group 3)

4.4 Project 4: Magnetism

Group 4 explored the concept of magnetism and attraction and repulsion, where arbitrary positions of nodes representing different buildings are adjusted, relocated and optimized based on attractor points developed in Grasshopper that denote relative weights of multiple objectives such as shading, wind flow and site accessibility (Fig. 4). The students worked with each of the objectives to satisfy the required contextual and environmental conditions, and then specified an adjusted location for each of the building components of the masterplan. The specific location for each of the buildings was justified and optimized according to the students based on the relative weights and strengths among each of the variables they set, such as shading and thermal comfort, accessibility and circulation, wind flow and other dimensions. They then attempted to work on the level of each of the individual buildings in order to achieve the concept of magnetism and attraction in terms of circulation paths, adjacency and spatial relationships among detailed functional spaces. This varied according to building type and design concept.

Fig. 4. Master plan using attractor points in Grasshopper to express the concept of magnetism, connectivity and accessibility (Group 4)
5 Case Studies

In the following subsections, we discuss in detail two of the group projects (group 1: responsiveness, and group 2: expression of time), with specific attention to the relationship between the emergent formal representations and the dimension of design autonomy within the explored parametric generative design systems.

5.1 Case Study 1

As mentioned in the previous section, Group 1 developed the concept of responsiveness in their group and individual work. As their concept was to create a multiple objective responsive and intelligent system, the group had to use more than one parametric design strategy. They decided to use two strategies: Kangaroo physics, and swarm intelligence systems.

In Grasshopper, the group used Kangaroo physics in order to quantify the bonds between the different elements of the master plan and simulate those bonds as either attraction bonds or repulsion bonds, as some spaces were assumed to be “attracted” towards some spaces and conditions, while others were “repelled”. This process of attraction and repulsion of particles until equilibrium is achieved represents the building and their location within the project site, where “equilibrium” is achieved when the location of each of the buildings is set with respect to the different environmental and contextual factors.

The group also implemented swarm intelligence to develop a guiding logic for the form generation and organization of each building within a unified formal language. This logic depended basically on permutations between three main variables: alignment, cohesion and separation (Fig. 5).
Applying different values and relative weights for those variables yielded infinite alternatives and 3D configurations. At first, the students explored these possibilities and their consequences, and how the formal outcomes reflected on the overall design solution. They then developed a justified logic for the specific five buildings in their master plan such that the values they assigned for those variables generated the required form using a rational and intuitive process, where later modification of those values could be easily comprehended in terms of its formal, functional and spatial consequences (Fig. 6).

For example, the exhibition building and shopping mall were consciously assigned higher separation values, as the nature of those building types was seen by the students as requiring more segregation, spread and distribution of horizontal spaces through a main circulation element. The hotel and office building towers were given higher alignment values, as they were seen to require vertical alignment and stacking of modules and spaces in a monotonous and repetitive fashion. Cohesion values were relatively lower than the other values, but were assigned the highest value in the shopping mall to denote the importance of the inner circulation spine as a binding element in the building space configuration.
By modeling the buildings with these variable relationships, the students took their design into a deeper level of evaluation. Within those variations and evaluation tools in Grasshopper, the students varied the number and distribution of structural elements, their cross sections, the horizontal inclination of the glazed walls between structural elements in response to orientation and sunlight. They used Millipede for structural evaluation and Ecotect for evaluating solar exposure (Fig. 7). Then they started documenting their work and extracting the necessary plans and sections using Autodesk Revit.

Fig. 6. Permutations between swarm intelligence variables developed by Group 1 to generate form for each of the buildings

Fig. 7. Structural analysis (in Millipede) and solar exposure analysis (in Ecotect) conducted by Group 1 for the exhibition building
Although the students seemed “in control” of the logic of the generated emergent forms, where they could consciously develop a unified grammar and 3D configuration for each of the five projects, in addition to conducting their environmental and structural studies further, their designs did not go further in terms of design development and detailing, as the formal approach was not sufficiently grounded in spatial and functional requirements (Fig. 8).

Fig. 8. Documentation and rendering of shopping mall building (Group 1)

5.2 Case Study 2

The students in Group 2 initiated their analysis with maps and diagrams exploring a number of possible user behavior and activity scenarios along specific daily and seasonal durations of the exposition center operation (Fig. 9).

Fig. 9. Analysis maps and diagrams studying user behavior along expo time schedule (Group 2)
The meta-ball systems that the group implemented for their analysis were based on cell divisions and generative forms inspired by natural formations (Fig. 10). The students began to work with the three elements they identified in their conceptual phase, which were: quality of spaces, spatial experience, and playing with light.

Fig. 10. Transformations of meta-ball agents in Grasshopper

The students used Grasshopper to simulate the design after studying transformations of meta-ball agents and their desired directions, starting by scripting a master pattern and developing it to create the final form (Fig. 11). The value of the agent change and its directions varied based on building function and type (Fig. 12).

Fig. 11. Experimenting with potential forms and circulation patterns

Fig. 12. Examples of resulting forms for the shopping mall and office tower
Following the form generation process, the students began to conceptually evaluate the produced forms. They extended their system autonomy to a level of detail where they could explore detailed design and development. This was the primary focus of their investigation. While the students did not fully explore opportunities for further development of the meta-ball concept, they jumped directly into spatial adjustment and functional detailing (Fig. 13). They explicitly expressed a need to be “in control” of understanding and detailing their designs, without much exploration into further emergent possibilities.

Fig. 13. Detailed architectural documentation for the shopping mall building (Group 2)

6 Discussion

In general, the results showed throughout all the observed groups of students that using the parametric and generative tools allowed for a larger pool of possibilities for design search and exploration in the very early phases of the design process, especially at the level of collective work. As students moved more into their individual work and design development phases, approaches largely varied. Some groups succeeded in developing their master plan and individual designs through a coherent and informed process, while others demonstrated full segregation between the formal representation and the subsequent design development. Section 6.1 outlines how we see the parametric design process between emergence and autonomy based on this study. Section 6.2 proposes further work and poses future research questions.

6.1 Parametric Design between Emergence and Autonomy

Although results cannot be fully generalized from such a limited study, it can be argued that there were much richer nuances in this parametric design exercise between design autonomy and formal emergence than the presumed firm dichotomy. Both were catalysts for design search and exploration. It cannot be explicitly stated that either were dominantly visible in the process. From our understanding, these nuances resulted from a number of factors, each of which had a direct or indirect impact on the nature of the process. These include: 1) the point of conceptual departure, 2) user experience and background, and 3) algorithmic thinking.
Point of conceptual departure. Each of the student groups typically had a different conceptual departure for their design projects. Group 1, although presenting an approach involving responsiveness, had originally adopted a more formal approach which was more biased to the capabilities of parametric and generative design systems rather than a conceptual parti as required from the exercise and objective of the design studio. The group thinking was mostly directed from the very beginning towards using multiple systems in conjunction, including swarm intelligence, cellular automata, Kangaroo physics and other systems. The architectural concept came actually as a post facto process when the students realized and were informed of a bias to using the tool per se versus using it to implement an architectural concept. This bias impacted the choice of the computational approach and tools, and guided the students throughout the phases of the project, regardless of a coherent set of design guidelines. This was clear in the design development effort, where the formal exercise consumed more time than the actual development and refinement of aspects of spatial quality and functional requirements.

The point of conceptual departure in group 2 was on the other end of the spectrum. The group spent a considerable amount of time in the early conceptual phases searching for an architectural concept and an intangible element that they could later express in the computational tool. The notion, expression and representation of time – in its different interpretations and connotations – was an intriguing concept for the group, and was a driving force for the overall conceptual structure of the project in its collective and individual format. The computational methodology and tool always came as secondary for the group. The process was always driven by the conceptual approach of expressing time rather than the form of the meta-balls which presumably represented that approach. The group continually searched for processes and structures in the tool – although often unsuccessful – that could augment that conceptual approach.

Group 3 departed from a specific environmental consideration, which was wind flow, and continued to augment the idea of flow-ability through other natural and behavioral dimensions in the surrounding environment. This conceptual departure highly affected the resulting forms as well as the selection of the necessary computational tools for modeling and simulation. The group however was fixated in terms of design development, as the initial developed forms remained unchanged for a considerable time. Individual attempts to develop the same conceptual approach in much more detail in each of the individual buildings were also limited.

Group 4 departed from an urban design concept related to connectivity, accessibility, as well as some environmental considerations, which they coined magnetism. In this approach, as in group 1, the students capitalized primarily on the software capabilities in terms of allowing for a justified adjustment and relocation of building elements as nodes in the project site based on attractor nodes and parametric interrelationships. As the students continued to develop their individual projects, this approach was not so evident or translated sufficiently, and all went separate ways.

User experience and background. Background and tool expertise played an important role in how parametric and generative design was experienced in this exercise. All student groups had prior experience using parametric design tools, but students belonging to group 1 were the most proficient. In their research of design
precedents, they explored the projects that used multiple and complex generative systems. This provoked the team to explore computational tools to their maximum potential and to explore different generative design systems and their capabilities. They investigated in depth cellular automata, swarm intelligence, kangaroo physics, and genetic algorithms, and went beyond the course objectives. They did not only use Grasshopper to develop their initial cellular units, but also explored and used Processing to develop code for the swarm logic. This explains some of the bias this group demonstrated in terms of precedence of computational logic and formal representation and emergence versus down-to-earth architectural concept generation and design development.

The other three groups however were less proficient in parametric modeling and using generative design tools. Moreover, some of the students could not absorb the fact that parametric design methods could help them manifest their designs from inception and throughout development. They expressed the need to be in full control of their designs throughout the process, without ironically being limited in the overwhelming space of emergent outcomes and formal representations that forced many of the students out of their comfort zone.

**Algorithmic thinking.** One of the main challenges in this exercise was to realize and materialize intangible architectural concepts using parametric and generative design systems and tools. For the students involved in this exercise, this presented a big question mark: how can intangible concepts such as flow, time, magnetism and responsiveness be translated into lower level input parameters and more tangible components that represent those concepts and approaches? After some preliminary testing and exploration with the available software tools, most of the students began to realize that there was no straightforward way of performing this convoluted process, and that parametric design tools were not tailored for their method of design thinking, but required an explicit way of algorithmic thinking and a logical breakdown of the required concepts and approaches into parameters, values, constraints and variables in order to come up with tangible solutions. This was not typically an easy task for all groups. There were three main approaches attempted by the students in this challenge. Students who were proficient with the tools could develop a clear logic and breakdown of concepts into explicit parameters and constraints, as was the case with the students of group 1. Others developed workarounds, such as students of group 2, who worked with a higher level computational concept such as meta-balls, and developed a separate logic for the form generation procedures and outcomes of their building designs. The approaches of groups 3 and 4 featured a complete segregation between the intangible concepts and the low level computational techniques implemented to achieve those concepts, and relied more on conventional design thinking methods in their design development exercises.

### 6.2 Implications and Future Work

Now back to the original question of this study involving parametric and generative design systems: does a dichotomy exist between the emergence of innovative formal representations on the one hand and the conscious process of generating and
developing an architectural concept on the other? According to the demonstrated results and observations, there is no such clear dichotomy. The ability to visualize and generate complex morphological representations can guarantee an in-depth understanding of the essence of architectural concept generation when aided by algorithmic thinking rather than being fully biased to the capabilities of generative design tools. At the same time, the development of design ideas can be fully exploited by emergent formal representations that offer a multitude of possibilities.

Implications for design and CAAD education are numerous. The focus on parametric and algorithmic thinking rather than tutorial sessions or software tool training is evident. This has its ramifications on the structure of CAAD curriculum in general, both at the level of CAAD courses and workshops, and digital design studio. The integration of parametric thinking – rather than just modeling – and form generation as a bottom-up approach – rather than a purely formalistic top-down approach – in design studio becomes more and more pressing. These new ways of thinking should include form as one dimension of many in the concept generation and development process, instead of an authoritarian element within which every other aspect of the design idea has to be blindly accommodated. Students should learn how to explore conceptual structures in computational tools, and not just parameters that drive a totalitarian form making process. A rather form finding approach requires that students incorporate different datasets and ideas early on in the process. The role of CAAD software vendors is not to be taken lightly in this context. A higher level understanding of relevant dimensions of architectural quality, such as the notion of space, complexity, circulation, adjacency, density, abundance, and other concepts should be explicitly embedded and integrated within computational tools to allow for a wider space of design search and exploration.

Conclusion

This paper reported on the process and outcomes of a digital design studio that explored the relationship between the emergence of innovative formal representations and design autonomy while using parametric design systems. It was observed that no clear dichotomy exists between both aspects, but rather a complex relationship that is highly affected by three important factors: the point of conceptual departure, user experience, and algorithmic thinking. The study concludes that design studio should incorporate algorithmic and parametric thinking rather than top-down form making approaches in order to integrate form as one of a multitude of dimensions of architectural quality to inform the design ideation and development process.

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Parametrics applied to Urbanism

Ronaldo Luiz Silva and Maria Carolina Mazaviero
Universidade São Judas Tadeu
arquitetur88@gmail.com, mcarolmazi@hotmail.com

Abstract. This research aims to analyze the potential offered by parametric urbanism to increase efficiency and the quality of urban design proposals. In parametric design, the template can be changed throughout the design process, allowing to generate and test lots of versions without the need to return to the starting point of the project. The introduction of parametric design urbanism has great potential because several aspects pertaining to urban design such as density, use, shape, space and type can all be defined parametrically. Thus, this research aims to understand and analyze this theoretical procedure and contemporary methodology of urban design associated to new technologies. It intends to analyze the advantages, disadvantages, applicability and improvement possibilities of this new way of designing the scale of the city and Brazil.

Keywords: Parametric Urbanism, Urban Project Methodology, Digital Design.

1 Introduction

The purpose of this article is to understand and analyze the theoretical procedure and contemporary methodological in urban design associated to new technologies, which is called Parametric Urbanism. This new trend is based primarily on parametric design systems, already widely used in the aerospace and automotive industries, in which the focus of interest is not in the form itself, but the parameters that generate it. The transfer of these technologies for architecture and urbanism is well known as parametric urbanism [SILVA; AMORIM, 2010]. This non-traditional method of urban design allows greater flexibility and variety of models. Thus, as an alternative to the traditional methodology, it allows a better control of the entire process, since the software tolerates changes during all stages of the work.

From this, and from the case study analysis of projects that have been implemented using this new architectural design method, we intend to analyze the advantages, disadvantages, applicability and possible improvements to this new way of designing in the city scale, as well as its applicability for the Brazilian cities. Importantly, this study is still under development as a research paper during the undergraduate course. This article, however, seeks to elaborate the theoretical basis underlying and supporting this research.
The computational advances of the last quarter of the twentieth century, which enabled the introduction of new technologies in the design process, has required a new way to deal with the traditional method of working of architects and designers [Kovaleric, 2000]. This new way of designing is the ability to produce information that can be manipulated digitally, and from this point, developing analyzes and simulations on any quantitative or qualitative aspect of the project. Mata [2003] has demonstrated this in her research that, among other issues, analyzed different types of digital architecture, unraveling the methodology adopted in each case, showing how the use of parametric allows information management and integration that is possible between different disciplines in a collaborative system of continuous architectural design development. Thus, this method increases the possibilities and solutions in different subjects, from more technical character as the acoustic, thermal comfort, structures, streams, etc., as well as relevant elements to the project, such as socioeconomic and cultural aspects. On this, the author adds that this practice allows a greater variety of solutions to the same problem, permitting to the architect a more favorable condition to experiment with different scenarios, "for designers these technologies provide the opportunity to have other areas and responsibilities such as data capture, data evaluation, optimization of solutions and simulation of planned results" [MATA, pg.11, 2010]. Therefore, that architectural and urban design method seems to have a great efficiency in the production of simulations and adaptations of solutions to be achieved in a project, greatly increasing the professional experimentation capacity.

From the analysis and optimization of results produced and tested during all phases of the project, the decision-making become more clear and informed on analytical data, making the whole process less intuitive and reducing the incidence of formalistic and superficial solutions. It expands, therefore, the possibilities of solutions to a given problem, moving away from the traditional and subjective form of traditional design thinking, as well as promoting new logic designs from the relationship of various systems [Celani, 2012].

2 Cases

As exemplary cases for the application of computational tools to urban planning, we chose two iconic projects that are distant in time and space and, therefore, they allow an analysis of the evolution of this design methodology applied to the city planning and urban design. The first is the Kartal-Pendik Masterplan in Istanbul, developed in 2006 by Zaha Hadid Architects, and the second is the design Flowing Gardens, developed in China by the Plasma Stúdio team in 2011.

In common, the analyzed projects explore a basic element of the traditional method of urban planning: the circulation system that, due to growing problems of mobility and its effects on the development of the contemporary city, has become a structuring element of almost all new projects for cities. The organization of flows has become a very important component for the development and implementation of any urban development policy, with particular concern for areas that suffer from a spontaneous swelling of the existing urban fabric, especially those with a steep and uncontrolled growth.
We also observed in the case studies that resulting grids from generative processes have the flexibility to simultaneously satisfy various circumstances; since their design and performance are obtained from analysis of various parameters, making them more adaptable to the various conditions, such as environmental, formal and functional.

In the masterplan for the Kartal-Pendik [Istanbul, 2006], the Zaha Hadid Architects developed the urban design from a method known as Hair System in order to optimize flexibility and circulation system. By definition, Hair System is a mesh or a branched grid without formal default setting because its configuration is the result of analyzes and simulations from several variables and implied specific and unique to each location and proposed project. Therefore, this resulting character allows the hair system becomes a living element, reactive to the demands and structuring the project, releasing the urbanist a real gain of possibilities for solutions and redesign urban settings. Therefore, it is not a formal solution to a problem, much less of a model that can be replicated in many places and independent of context, as a generic solution or a totalitarian and universal answer.
The project developed in Kartal-Pendik has a high flexibility that the method takes. The resulting grid has great elasticity to fit the topography of the region and ensures integration and fluidity with the existing grid in areas outside the project.

Fig. 2. Hair System deployed in Flowing Gardens. Source: www.plasmastudio.com/. Accessed 30/01/2015.

The second case study, which is another interesting example of a circulation system optimization also based on complex hair system methodology is the design Flowing Gardens, [Xian, China, 2011] developed by Plasma Studio together with Groudlab office. The project won an international tender for the construction of a pavilion that will house an horticultural exhibition.

The project proposes the creation of a mesh composed of a complex network of branches that operates in a number of scales associated with landscaping, creating micro-regions that will changing as the observer moves by the project, breaking the monotony and giving vitality to the grid. In both projects, we note that the matrices formed from parametric analyzes assume a more fluid and organic configuration, following a rhizomatic logic.

When we analyze the concept of branched or rhizomatic grids, we must mention the contributions of the research carried out by Frei Otto. From studies conducted between 1958 and 1960, Frei Otto analyzing a system that he designated as minimal path system [CRUZ, 2012]. The analysis was made from experiments and simulation
elements of nature, such as the structures resulting soap bubbles "As mentioned above, the soap film surfaces to reduce the minimum required configuration, thereby revealing the shortest path to create a form" [CRUZ, pg.218, 2012].

The concept of minimum paths were to create branched meshes always aiming to create a route that offers better performance in many ways, whether by optimizing the circulation, or through the need for fewer materials for its implementation, greater flexibility of use. Thus, his research methodology incorporating the concept of projetual higher optimization.

![Fig. 3. Paths experiments minimum. Source: OTTO, 2011.](image)

2.1 Application of new paradigms to the informal city intervention.

The incorporation of generative systems to urban design methodology seems better suited to the complexity of the contemporary city, especially when one considers the informal portion of these cities [Romano, 2010]. Elizabetta Romano together with Giancarlo Tonoli developed a research called Genetic Code of Slums, in which they developed a method to identify the logic of the so-called informal city, recognizing their complex relationships that make these spontaneous urban areas generate problems difficult to solve and a mismatch compared to traditional lattice grid, widely
used in Brazilian’s urban projects. From there search on the logical expansion of the informal city, a parametric script was generated that would adapt the socio-reality of that particular site. After identifying the agents who acted as process forces, the authors understood the complexity of these clusters, which is due to the fact that all the components of its spatial morphology, social, cultural and economic character are directly linked, promoting constant changes and establishing relationships between its inhabitants, “assuming that the city is not a finished system, but a living organism in constant-development” [ROMANO, pg.02, 2010].

The authors argue that, given the formation of these settlements based on accommodation of the needs of the community, the space resulting from the occupation should be able to adapt to new requirements and accommodate varied use of programs. Therefore, they say, interventions in these areas that do not take into account such complexity, fatally would fail. The application of the resulting algorithm of this investigative process allowed the authors to conclude that the use of a design methodology with more analytical and flexible resources allowed a closer result than is actually required for the complex organization of informal areas in Brazilian cities.

3 Final thoughts.

The resulting methodology from the application of computational tools to urban design and city planning extends the possibilities for solutions to the city, allowing urban regeneration projects in areas with complex features, like the Brazilian favelas, resulting in designs that are more consistent and that best fit the territorial conditions and the real needs of the inhabitants. The study of international examples, as well as an analysis of informal areas morphology, seem to point to the fact that the traditional orthogonal grid widespread by modern urban planning, due to its totalitarian rigidity, does not have the necessary performance for urban projects in these areas, without the loss of the very identity of the informal city.

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Parametric analysis in Islamic geometric designs

Carlos Barrios and Mostafa Alani
Clemson University
{crbh, mostafh} @clemson.edu

Abstract: A method for the analysis of metamorphosis in traditional Islamic geometrical patterns using a parametric model is presented. The method uses traditional Islamic geometry as a starting point and performs an analysis of pattern’s fundamental units and cells and presents metamorphosis operation based on parametric variations of geometry and color.

Keywords: Islamic Geometric Patterns, Pattern Generation, Parametric Modeling, Color, Parametric Variations, Metamorphosis.

1 Introduction

A considerable amount of research has been conducted to answer the question of how to create both traditional and new Islamic Geometrical Patterns (IGP). One of the biggest challenges is the lack of comprehensive manuals from the original designers of the geometrical patterns since some of the traditions date back many centuries and was transmitted by word of mouth. Some scholars have attempted to answer this question turning their attention to the process of replicating traditional patterns and making inferences by observation and analysis. Others have aimed to create new patterns from scratch that look similar to the traditional counterparts using the rules of symmetry groups in the plane. Recent studies show how computation may enrich the understanding of the IGPs by simulating the methods presumably used by the original artists and craftsman while creating new designs that might have not been done before.

In the last few year parametric modeling has served the purpose to create digital models with variable geometry for design. So far there are limited applications of parametric modeling outside the realm of generative design. This is perhaps due to the unpredictable manner in which design exploration is conducted in the context of computational design, thus making parametric models ideal for the initial phases of the design process when many decisions are yet to be made. It helps the designer to know that changes to the model can be made with ease while certain decisions are still temporary.

In this paper we aim to use parametric models as aids in analyzing traditional design patterns. The focus on the study herein presented discusses a methodology that uses parametric models to analyze Islamic geometry and the traditional patterns of
Islamic decoration and reconstructs the traditional patterns and new original IGP designs in the language. Our exploration focuses on two aspects of the original designs: the geometry of the patterns and the use of color as a parametric attribute in the pattern. Furthermore, we explore the implications of the parametric variations in the topology of the IGPs. This paper presents and discusses an approach towards the use of parametric models to study traditional design patterns and create new designs in the language by means of metamorphosis.

2 Analysis of Islamic Geometric Patterns (IGP)

In general terms, Islamic Geometric Patterns (IGP) are decorative elements that make extensive use of geometric shapes. According to Syed Abas and Amer Salman (Abas et al. 1995) Islamic geometric patterns contain any of the following:

1. Arabic calligraphy
2. Created between 900 AD and 1500 AD by Muslims or non-Muslims in a society where the common practiced religion was Islam
3. Patterns derived from Arabic calligraphy or traditional patterns

For the purpose of our research we build upon the last definition to explore traditional IGPs by observation and use the results of this analysis to derive new IGPs from existing geometries.

Our process starts with screening a set of selected IGPs and decomposing the existing traditional Islamic geometry by examining at the two most important qualities of traditional IGPs: the seed geometry or basic unit for the pattern which we will call the cell; and arrangement or tessellation which is the actual pattern generated by the repetition of the cell in one of the 17 plane symmetry groups. Figure 1 shows a pattern and the corresponding cell. When these elements are parameterized it is possible to make variations to generate new patterns. Variations can be done by making changes in the geometry of the cell and the tessellation. For the purpose of this research we will focus on making parametric variations on the cell only. Both Issam El-Said (El-Said et al. 1993) and Rima Al Ajlouni (Al Ajlouni 2012) have clearly distinguished between the repeat unit or cell, which is the basic geometrical composition, and the pattern structure, which is the product of systematically repeating the cell.
The Fundamental Unit

In most cases, it is possible to examine the IGP cells and find symmetry within the geometry of the cell. It is also possible to dissect the cell into smaller units until the non-symmetrical part is found. We call this part the fundamental unit. The fundamental unit in the cell is the group of geometrical elements with non-repeating components (Alani 2015). **Figure 2** shows a cell and the extraction of the non-symmetrical geometrical component, the fundamental unit. In principle every cell for every pattern will contain a single fundamental unit which defines the minimum motif that is not attainable with symmetry. For the present study, finding the fundamental unit is crucial since this is the place where the parametric variations will start.

**Fig. 1.** Islamic geometric pattern and cell

**Fig. 2.** Islamic Geometric Pattern (IGP), Cell and Fundamental Unit
According to Abas and Salman (Abas et al. 1995), the cell is the region with the motif that may be repeated to create the whole geometry, and the fundamental unit, that is also a repeated geometrical composition, are essentially dissimilar. The difference is that the cell creates an unbounded design while the fundamental unit does not. Therefore, we differentiate between the cell and the fundamental unit by the results they create when repeated. Because the method we are defining does need a completed geometry to begin, it is always a good idea to break down the steps of finding the fundamental unit by analyzing the parts of the geometry. The geometrical components of the Cells can be subdivided into triangular polygons that enclose the fundamental unit, with one of the vertices located at the center of the cell, and the other two vertices located at the edges of the cell. Figure 3 shows a cell subdivision with a corresponding polygon enclosing the fundamental unit.1

Fig. 3. Subdivision of Cell with polygon enclosing Fundamental Unit

There are no specific rules that govern the relationship between the fundamental unit and the cell; in fact, it actually depends on who originally designed the geometry. Aljamali (Aljamali and Banissi 2004) proved that point by breaking up the steps of creating Islamic geometric patterns into four stages: the planer surface stage, the divisional stage, the artistic stage, and the extension stage. The artistic stage is an important factor to consider in determining the fundamental unit. The combined cell units that contains the fundamental unit are defined as the fundamental region. Aljamali (Aljamali and Banissi 2004) takes the approach of defining the radius of the cell and the angle of rotation of the fundamental unit inside the cell.

Parameterization

Many scholars have done work analyzing the geometry of the IGP by isolating cells and populating them to reconstruct the corresponding pattern. Recently designers have used this knowledge to create modern versions of IGP designs from scratch. Such is the case of Al Bahar in Abu Dhabi, a 29 stories tower complex designed by Aedas. This award winning project features a double façade with a triangular pattern simulating a mashrabiya, a traditional Islamic lattice typically used to enclose second story large openings in houses and buildings. The method here proposed is able to do both simultaneously. By performing a post-design analysis of an existing geometry

1As a principle, cells can hold only one fundamental unit, although we have found some exceptions to this.
and parameterizing the geometrical elements of the fundamental unit, we are able to recreate the existing patterns and at the same time, produce new unique designs from the same parametric model. The proposed methodology does not create new geometries from scratch, but relies on the geometry of the existing IGPs. We create a parametric model and perform parametric variations on the existing Islamic geometry based on specific rules to control the results.

The first step is to isolate the cell to delineate the fundamental unit. The fundamental unit is found by decomposing the cell to its constructional non repeating components. This operation will generate a fundamental unit for the pattern, which is defined as the minimum motif that cannot be reached with symmetry. Once the fundamental unit is attained we proceed to reconstruct its geometry with a parametric model; a geometrical construct with variable attributes (properties) that allows the exploration of design variations with ease (Barrios Hernandez 2006). By defining certain rules that govern the parameters, the designer can to explore the patterns in a manual manner.

The variations performed on the fundamental unit will populate to the cell and consequently to the pattern. Thus, the parameterization of the fundamental unit will allow designers to manipulate the whole pattern. We have built a computer representation model to construct the entities of the geometrical patterns with modifiable attributes. The parametric model we constructed consist on parameterizing the geometrical points located inside the boundaries of the fundamental unit’s bounding triangle. Figure 4 shows the parameterized geometry in the fundamental unit.

![Parameterization of the Fundamental Unit for IGP cells for 4, 6 and 12 pointed stars](image)

**Fig. 4.** Parameterization of the Fundamental Unit for IGP cells for 4, 6 and 12 pointed stars

### Parametric Variations

Parametric variations are carried on the parametric model of the fundamental unit. These are done by moving the position of the free points to change the geometry of
the fundamental unit. As a result, the geometry of the cell and the design of the pattern is transformed. Our research revealed two possible outcomes from this particular parameterization: The first enables the preservation of the topology of the fundamental unit and consequently of the cell and, by extension, the pattern. The second outcome transforms creates a topological variation in the cells and corresponding patterns. Both outcomes have advantages and limitations when using them to study the design language of the IGP s, or when creating new designs, which are subject of current research. Nonetheless it is quite possible to derive new patterns from both of them.

Since the parametric model creates a very large number of geometrical variations it is reasonably impossible to show all of them. To see all of them would be impractical, hence designers typically select a representative group of instances that show enough variations and arrange them in a table or matrix form. As a consequence the parametric model becomes the container of all possible designs. We found that a convenient way to visualize the variations is through geometric metamorphosis. A Geometric Metamorphosis, or change in the geometry, provides a convenient way to explore design variations in the form of a timeline showing progressive variations in the parametric model. There are several advantages of applying this process. First, the changes are done in an incremental manner and one parameter at a time, thus providing continuity to the transformations. Second, it becomes possible for the designer to selectively extract the instances that are of interest. This process is akin to computer animation were the instances are extracted as key-frames while the rest of the variations are the in-between frames. These key instances or key-shapes can be frozen in time for further study. Figure 5 shows parametric variations of a fundamental unit and corresponding cells. Any of these instances can be selected to become a key-shape for further studies. In theory there are infinite key-shapes in any parametric model, as many as design instances. But it would be impractical to treat them as equal.

2While a very large, or even infinite, number of possible designs can be contained with a single parametric model, a typical problem is that designers are only able to see one at a time.

3Metamorphosis refers to a biological process that occurs in some living creatures in which changes to appearance occur. In our case we refer to changes in geometry.

4The idea of a key-shape refers to the state of the geometry at a particular point in time (Kolarevic 2004).

5The importance of a key-shape is given by the designer and there are many ways in which this can happen. This would constitute a whole research in itself beyond the scope of the present study.
Fig. 5. Parametric variations of the Fundamental Unit for the six point star cell. Anchored points are fix and constrained points move along the green line in the bounding polygon

3 Metamorphosis

In this stage of the process we try to move beyond the re-construction of the patterns in order to explore the geometry and the outcomes of the variations of the parametric model, both in the cell and the pattern. We had discussed before that the IGPs can be produced by imitating the existing traditional patterns, or that new patterns can be created from scratch. Since our parametric model is able to do both, the metamorphosis will be used to conduct an exploratory study of the geometrical transformations of the cells and the implications on patterns to reconstruct historical IGPs as well as new patterns. We believe that this will help to enhance our understanding of formal qualities of IGPs in relation to the cells and fundamental units.

The experiment will be divided into two categories based on the two aforementioned outcomes: 1) fixed topology; and 2) variable topology. On each of these categories two different kinds of parametric variations will be conducted: a) a parametric variation on geometry; and b) a parametric variation on color. The combination yields four (4) possible kinds of parametric variations as follows:

1. Fixed Topology: parametric variations will change the geometry but not the topology of the cell
2. Variable Topology: parametric variations will change the geometry and the topology of the cell
3. Fixed Topology and Color: Color is introduced as a variable attribute in the parametric model with the fixed topology.
4. Variable Topology and Color: color is introduced as a variable attribute in the parametric model with variable topology.
In the next few sections we will look in detail at each of these possible variations and the effect produced by them when applied to generate the IGPs.

**Rules of Spatial Transformation for the Parametric Model**

Of the three kinds of points used in the parametric model, anchored (A), constrained (C) and free (F), there are some rules to follow on how they will be varied. 1) Anchored points (A) are fixed and cannot move. 2) Constrained points (C) can travel toward and against the center of the cell along a line. 3) Free points (F) can move anywhere inside the boundary of the fundamental unit. All the points located on the outer edge of the repeated polygon are considered anchored points, and the rest are either constrained or linked constrained. One final requirement is that all parametric transformations will start on the same stage of the parametric model. This will help keep track of how parametric variations alter the cell and the IGP. We call this the initial state.

**Fixed Topology**

In the first stage we perform parametric variations where the new geometry should be always be topologically identical to the starting point of the variations. In other words, the total number of points and edges remain identical at every stage in the parametric variation. While the geometry changes, any parametric variation should not result in a topological transformation.

The geometry of the new designs can be generated by adhering to the following rules, for all the points within the fundamental region: 1) Point overlap is not allowed; 2) line overlap is not allowed; 3) Intersections are allowed; and 4) Points should not leave the fundamental region. Figure 6A shows parametric variations in the fundamental unit for two examples, the six pointed star and the eight pointed star. We see a change in the geometry of the cell and the corresponding IGP. While the geometry changes, the topology remains identical in all designs. Figure 6B shows the corresponding IGP generated by the parametric variations.
Fig. 6A. Parametric variations of cells and fundamental units of the six (6) and eight (8) pointed stars.
Fig. 6B. Parametric variations of patterns for the six (6) and eight (8) pointed stars IGPs. Note how the topology of the pattern does not change.

Variable Topology

In this section we discuss the second kind of parametric variation. In this case the variations will result in a new geometry and a new topology. We start to perform parametric variations to the initial state of the parametric model. The initial state should be always be topologically identical to the starting point of the variations.
New geometries can be generated by following rules: 1) At least one point should overlap; 2) Lines are not allowed to overlap; 3) Intersections are allowed; and 4) Points should not leave the fundamental region. Figure 7A shows parametric variations in the fundamental unit for the previously discussed examples, the six pointed star and the eight pointed star. In this case we see a change in the geometry of the cell and in some circumstances a change in the topology as well. This propagates to the corresponding IGP as shown in Figure 7B.

Fig. 7A. Parametric variations in the fundamental units of the six (6) and eight (8) pointed stars. Notice variations in topology.
Fig. 7B. Parametric variations in the six (6) and eight (8) pointed stars IGPs. Notice variations in the topology
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Fig. 7B. Parametric variations in the six (6) and eight (8) pointed stars IGPs. Notice variations in the topology.

For the six point star, there is only one parameter to control because it contains only one constrained (C) point. However, the eight-point star has two points to control, one is a constrained point (C) and the other is a free point (F). This extra degree of freedom results in more geometrical variations as we will discuss later. An important aspect is to note the changes in topology of the IGPs as noted in Figure 7B. The number of points and line segments can change when points collapse and lines overlap.

Fixed Topology and Color

Another type of variations occurs when we introduce color as a variable attribute. In this case color is added as a parameter in the model. The use of color in the cell will result in a change of symmetry and will have an effect on the overall pattern. For the purpose of our exercise we will only use one of the patterns of the six pointed star.

Take for instance the cell in Figure 8 and see how the variations in color changes the symmetry group of the cell, and consequently the pattern. While the geometry remains unchanged, the color schemes in the cell changes the patterns, therefore generating a new one. In our example color becomes an attribute that is subject to...
parametric changes. Color can be used as a way to distinguish patterns with similar geometry but subtle differences. Color can also be used to generate variations in the pattern and break the regularity of the symmetrical IGPs to create semi-periodic patterns out of regular geometries, or even irregular patterns. Color can also be used as a design attribute to indicate changes in materials, textures or other properties in a building, to indicate layers in a composition, or to design elements in a Figure/ground manner.

![Parametric variations of the six (6) point star cell due to changes in color and corresponding patterns.](Fig. 8)

**Variable Topology and Color**

Introducing color as a variable attribute to the variable topology case can be a little more complicated. This is due to the fact that for this case there are two independent parameters that can change the symmetry group of the IGP. When color is introduced
to the fixed topology IGP, all colors in the cell will be preserved in the pattern. This is not the case with the variable topology.

In the variable topology, some of the parametric variations will produce new shapes that might not have an associated color. Or some of the actual colored shapes will disappear when the parametric transformations evolve to change the topology. If colors represent specific properties they may not be present in the pattern. This does not mean that it might not be useful, but it probably requires an extensive study of the implications of the parametric variations in the cell and the corresponding patterns when the topology of the cell and the pattern changes. We found that this might have an application in analyzing the evolution of the IGPs in time, or when making comparisons between different IGPs.

**Continuous Metamorphosis**

In section 2.3 when parametric variations where introduced, we spoke about extracting some of the designs as *key-shapes* for further analysis. This process will allow the isolation of a specific design or group of design instances of interest. However, in research we are also drawn to look at the process of continuous and discrete transformations. When parametric variations are done in very small increments the result is akin to morphing. Morphing is an effect used in animation to actively change one form into another in a seamless transition. Morphing has also been used in computational design to explore intermediate stages between two different shapes. Morphing is studied in mathematics as part of set theory and topology.

Morphing caught our interest in this research as a tool for finding relations between similar and different IGPs as it would allow us to stop the transformation process at any convenient time. To morph the IGPs, we wrote a code that started with two extreme design conditions and created all in-between transformations in relation to a timeline. The program allows the user to assign different values to the parameters at different points in time and let the computer find all intermediate stages. Furthermore, the program allows the user to freeze (pause) any instance for further analysis.

In Figure 9 we present a few snapshots of one of the animations of the six point star cell morphing procedure. In this example we start by selecting a cell unit and determine the point types. Anchored points are drawn in red, and constrained points are drawn in green (Fig. 8A). The code proceeds to *collapse* all the constrained points to the center of the polygon (Fig. 8B) where all green points are at the center of the cell.

The next step is to release one of the green points at a time (Fig. 8C) and have the point travel away from the center of the cell until it reaches the outer boundary of the cell (Fig. 8D). Once this happens, a second constrained point is released and the first point travels towards the center of the cell (Figs. 8E-8F), until it reaches the center of the cell (Fig. 8G) to start the process again. This back and forth motion of the constrained points produces all the variations according to the preset number of in-between units in the code.
A point can travel a specific distance within a specific preset amount of time, thus making the morphing process go faster or slower. The time and distance are variables making the morphing process smoother. The point stops if it intersects a line, overlaps another point, or the point leaves the fundamental region. This procedure will allow us to explore the design domain all possible designs within the selected boundaries. As a result we can obtain not only the original geometries in the IGPs, but many others that are not historical designs. Figure 10 shows a few of the key-shapes of this particular cell where the IGPs enclosed in a green box are existing IGPs and the others are new designs.
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Fig. 10. A selection of key-shapes from a morphing process of the IGPs based on a six pointed star. Shown here are some of the original IGPs indicated with the green square, and the others are new patterns.

4 Discussion

The question that needs to be asked at this point is, *is it possible for a key-shape of one geometry to be equal to an existing Islamic geometry?* The answer is yes. In the case
presented in Figure 10 we found that of the selected 16 key-shapes, 7 of them exist. The rest are considered new patterns.

Moving an anchored point (A) can break the continuity of the pattern as well as create additional intersections. In addition to changing the topology, this yields different results, some interesting and some chaotic. This is the subject of further studies.

By exploring all possible combinations of the geometric components within a pattern, it will be possible to identify the desirable systems of proportion for a specific case. It is possible for two distinct geometries that exist in traditional Islamic patterns to have same geometry and topologically, but each one represents a different point in time. Consider this, El-said, in his book Islamic Art and Architecture, demonstrates how to generate an eight-point star. Later in the same chapter, he explains how to generate the octagonal pattern. In other words, he shows two different geometries with two different set of rules to generate them, but both have the same topology and belong to the same symmetry group. El-said expresses the eight-point star as A:B:A, which represents the proportions of the constructional grid, while he expresses the octagon as A+B:B. However, using the method presented in this paper, it will be possible for a designer to manipulate these proportions to reach the octagon from the eight-point star and vice versa with the morphing method (El-Said et al. 1993).

If the original IGPs can be derived from the morphing process, what else can we derive? The answer is that a seemingly unlimited number of geometries can be derived by considering fractions of distance in relation to time. Now, to differentiate geometries, we need a new system that can classify based on when they occur. This predicament implies the second question as to considering the new generated IGPs as genuinely Islamic. If we consider the third proviso that prescribes Islamic patterns as ones derived from other Islamic patterns, then we can say with confidence that the new IGPs are in fact Islamic. Furthermore, some of the new patterns seem to fit the visual imagery of the traditional Islamic counterparts, but this perhaps will require further studies to determine the degree of likeness to the traditional patterns. “Just like nature, there is a universal code, there must be one like this for architecture,” Lalvani (Lalvani 2010) said in a TEDx Brooklyn talk. This method is a step toward in finding the code of the original Islamic geometries, and in generating new geometries through a guided exploration of Islamic geometry.

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At the time of writing this paper, we have not found a match for an existing IGP for the other 9 key-shapes. However it is quite possible that they actually exist. On the other hand, we only selected 16 of many more key-shapes, thus it is possible that many more new designs can be created.
Acknowledgments

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The future of the architect’s employment

To which extent can architectural design be computerised?

Gabriela Celani, MayconSedrez, Daniel Lenz and Alessandra Macedo

University of Campinas

celani@fec.unicamp.br,
(mayconsedrez, danieulenz, alessandracelani)@gmail.com

Abstract. This paper was motivated by Frey and Osborne’s [1] work about the probability of different occupations being computerised in the near future, titled “The Future of Employment”. In their study, the architect’s profession had a very low probability of being automated, which does not do justice to the past fifty years of research in the field of architectural design automation. After reviewing some concepts in economics and labor, and identifying three categories of tasks in regards to automation, we propose a new estimate, by looking independently at 30 architectural tasks. We also took into account the reported advances in the automation of these tasks through scientific research. We conclude that there is presently a change in skill requirements for architects, suggesting that we have to rethink architectural education, so architects will not need to compete against the computer in the near future.

Keywords: Computerisation, design automation, architectural profession, architectural education.
Design Agency

Prototyping multi-agent systems in architecture

David Jason Gerber, Evangelos Pantazis and Leandro Soriano Marcolino

University of Southern California
{dgerber, epanatazi, sorianom}@usc.edu

Abstract. This paper presents research on the prototyping of multi-agent systems for architectural design. It proposes a design exploration methodology at the intersection of architecture, engineering, and computer science. The motivation of the work includes exploring bottom up generative methods coupled with optimizing performance criteria including for geometric complexity and objective functions for environmental, structural and fabrication parameters. The paper presents the development of a research framework and initial experiments to provide design solutions, which simultaneously satisfy complexly coupled and often contradicting objectives. The prototypical experiments and initial algorithms are described through a set of different design cases and agents within this framework; for the generation of façade panels for light control; for emergent design of shell structures; for actual construction of reciprocal frames; and for robotic fabrication. Initial results include multi-agent derived efficiencies for environmental and fabrication criteria and discussion of future steps for inclusion of human and structural factors.

Keywords: Generative Design, Parametric Design, Multi-Agent Systems, Digital Fabrication, Form Finding, Reciprocal Frames.
ModRule

A user-centric mass housing design platform

Tian Tian Lo¹, Marc Aurel Schnabel² and Yan Gao³

¹The Chinese University of Hong Kong
skyduo@gmail.com

²Victoria University of Wellington
marcaurel.schnabel@vuw.ac.nz

³University of Hong Kong
yangao@hku.hk

Abstract. This paper presents a novel platform, ModRule, designed and developed to promote and facilitate collaboration between architects and future occupants during the design stage of mass housing buildings. Architects set the design-framework and parameters of the system, which allows the users to set their space requirements, budgets, etc., and define their desired way of living. The system utilizes gamification methodologies as a reference to promote incentives and user-friendliness for the layperson who has little or no architectural background. This enhanced integration of a both bottom-up approach (user-centric/player) with a top-down approach (architect-centric/game-maker) will greatly influence how architects design high rise living. By bridging the gap between the architect and the user, this development aims to instill a greater sense of belonging to people, as well as providing architects with a better understanding of how to give people more control over their living spaces. The paper also presents an evaluation of a design process that employed ModRule.

Keywords: Mass housing, collaborative design, participatory system.
Structural design based on performance applied to development of a lattice wind tower

Marina Borges and Ricardo H. Fakury

Federal University of Minas Gerais
marinafborges@gmail.com, fakury@dees.ufmg.br

Abstract. This paper studies the process of parametric and algorithmic design, integrating structural analysis and design for the generation of complex geometric structures. This methodology is based on the Performative Model, where the shape is generated using performance criteria. In the approach, the development of complex structures is only possible by reversing the process of thinking to generate the form with established parameters for geometry, material and loading aspects. Thus, the structural engineer no longer only participates in the evaluation phase but also appears in the early stages, creating a process of exploration and production of common knowledge among architects and engineers. To research performance-based design, the development of a conceptual lattice for a wind tower is proposed. Thus, a system is made to generate geometries using Rhinoceros software, the Grasshopper plugin, and the VB programming language, integrated with stress analysis through the Scan & Solve plugin.

Keywords. Structural Design, Parametric and Algorithm Architecture, Structural Analysis, Performative Model, Lattice Wind Tower.
Parametric modeling of bamboo pole joints

Olivia Espinosa Trujillo and Tsung-Hsien Wang
University of Sheffield
arq.oet@gmail.com, tsung-hsien.wang@sheffield.ac.uk

Abstract. This paper describes the development of a parametric modeling system that enables the design of customized bamboo pole joints, where the geometry of each bamboo piece becomes the main design constraint. Rules of design are identified in traditional bamboo-jointing practice through the analysis of a bamboo catalogue. This knowledge informs the constructive principles of the system. Output data of the system successfully formulates the design of a customized bamboo jointing system. The effort of this paper suggests that further development of an application or software to facilitate the design of parametric bamboo joints is a feasible project that could help bamboo to have a solid presence in modern building industry. Lastly, the paper hints that transference of parametric technology is a promising domain that could potentially be applied to streamline the use of other natural materials.

Keywords: Bamboo, pole joints, design rules, parametric modeling.
Assisted construction of non-standard wooden walls and envelope structures by parametric modeling

Oscar Gamez, Jean-Claude Bignon and Gilles Duchanois
School of Architecture of Nancy
gamezboh1@univ-lorraine.fr, \{bignon, duchanois\}@crai.archi.fr

Abstract. We introduce a parametric modeling method in the field of computer-aided architectural conception, which aims to produce non-standard wooden walls and envelopes with CNC machinery. This method explores the application of polygonal cellular structures (as patterns) on facade and envelope interventions for new and old projects. We innovate by bringing the 3D production environment complexity into the conception model to improve the production of manifold woodworking items by CNC (Computer Numerical Control) 3D fabrication. A recent experimentation tests the entire workflow from parametric modeling to production of two full-scale prototypes. The results prove the range of inputs offered by the method to be functional, though it needs various improvements in order to optimize parametric modeling and digital fabrication procedures. Future research will focus on treating a wider range of joints via parametric modeling and deal with joint creation regardless wall deformation to expand the morphological approach of non-standard wooden walls design.

Keywords: Non-standard walls, Computer-aided architectural design, Wood construction, Parametric modeling, CNC fabrication, Mass customization.
Building information modelling (BIM)
The definition of semantic of spaces in virtual built environments oriented to BIM implementation

Michal Brodeschi¹, Nirit Putievsky Pilosof¹ and Yehuda E. Kalay¹

¹ Technion – Israel Institute of Technology
brodesch@technion.ac.il, nirit.pilosof@gmail.com, kalay@technion.ac.il

Abstract. The BIM today can be a provider of inputs to performance analysis of different phenomena such as thermal comfort, energy consumption or winds. All these assessments are fundamental to the post occupation of the building. The attainment of approximate information of how the future building would behave under these conditions will reduce the waste of materials and energy resources. The same idea is used for evaluating the users occupation. Through simulation of human behavior is possible to evaluate which design elements can be improved. In complex structures such as hospital buildings or airports is quite complex for architects to determine optimal design solutions based on the tools available nowadays. These due to the fact users are not contemplated in the model. Part of the data used for the simulation can be derived from the BIM model. The three-dimensional model provides parametric information, however are not semantically enriched. They provide parameters to elements but not the connection between them, not the relationship. It means that during a simulation Virtual Users can recognize the elements represented in BIM models, but not what they mean, due to the lack of semantics. At the same time the built environment may assume different functions depending on the physical configuration or activities that are performed on it. The status of the space may reveal differences and these changes occur constantly and are dynamic. In an initial state, a room can be noisy and a moment later, quiet. This can determine what type of activities the space can support according to each change in status. In this study we demonstrate how the spaces can express different semantic information according to the activity performed on it. The aim of this paper is to simulate the activities carried out in the building and how they can generate different semantics to spaces according to the use given to it. Then we analyze the conditions to the implementation of this knowledge in the BIM model.

Keywords: BIM, Virtual Sensitive Environments, Building Use Simulation, Semantics.
1 Introduction

Building Information Modeling is considered nowadays the most appropriate tool for the representation of architectural design and construction. BIM models are being widely used for building performance analysis, significantly in the area of energy efficiency. The outputs generated in those experiments can aid to improve the design, resulting in a considerable economy in the final product. Chang (2014) [1] demonstrated this hypothesis of simulating thermal efficiency system for windows could reduce operational costs. The same importance should be given to simulation of human behavior in built environments to evaluate whether the quality of design is coherent to the needs of an optimal operating.

The intention of this paper is to verify what are the relevant characteristics that should be represented in the BIM model for the simulation of human behavior. Although BIM models have a high definition in its parametric representation, there is still a lack of semantics. The semantic knowledge once represented in the model, enables achieving a powerful BIM, able to set more accuracy in the evaluation phase of building performance. Identifying the semantics of the spaces represented in the model makes it possible to identify the real function and use of each of them. The geometrical forms earn a meaning that permits to be recognized by Virtual Users (Steinfeld, 1992)[2] and (Kalay et al, 1995)[3]. The VU thereby manifest a behavior according to the context. The gap between what was expected in the project and real building can be narrowed since users are included in the design conception and representation phase.

Considering users preferences and reactions makes it more tangible to designers to adapt the project to human needs. The motivation of this study came from the interest in investigation the possibilities of using a virtual model as BIM to support a simulation of environmental scenarios of end users in a building before its construction. The proposed methodology was also developed to be adopted for the control and management of information generated in consequence of human activity, which are usually not supported in architectural projects and complementary projects.

The study case conducted here was targeted to evaluate the functioning and effectiveness of a healthcare facility design. Operational efficiency in hospitals is heavily influenced by the design of the built environment and by the location of some “problem areas” such as specific patient care spaces, departmental areas (nursing units, diagnostic and treatment units) and public areas (corridors, lobbies, waiting rooms) (Cohen U. et al., 2010) [4].

The purpose of this sort of evaluation is indeed to improve the design layout and specificities. A direct consequence of this enhancement is an improvement in staff performance, environmental comfort, time reduction of patient’s recovery, users’ satisfaction, rapid diagnosis and treatment, facilitate the flow of visitors and general better way finding. Healthcare facility projects demands a high degree of complexity in its operation. A special attention should be given to the flows. Patients, doctors, visitors access should be carefully considered due to of the risks of infections, emergency, privacy or for safety reasons.
It is expected, therefore, to contribute to the state of the art of evaluation and visualization features connected to BIM platform pointing the most appropriate and flexible techniques for human behavior simulation studies. However, allowing experimentation on this structure also enables the model to be submitted to other studies on hypothetical conditions, contributing to the understanding the advantages and disadvantages of the methodology adopted. Yet leads to proposals for future improvements.

1.1 Related work

Studies on methodology and simulation of the interaction human-environment have been performed as: pedestrian movement, crowd simulation and fire egress. Such studies attempts to understand how people react to different stimuli derived by the building in emergency cases. Other stimuli can also influence the use of the building; external factors such as temperature, noise and smells as well as the intrinsic characteristics of each user.

Through the observation of how manifest these reactions, conclusions can be drawn about what in the design is appropriate and what can be then improved. A knowledge-based model allows the VU to associate spaces to their meaning. Thus allows them to select such shorter routes, as to know for example which spaces are available to perform a given activity. To this end became necessary the development of a semantic model in which agents could perform a truer reading of the surroundings.

In the literature some approaches has been done of knowledge-based models oriented to Human Behavior simulation such as Tan et al (2005) [2], a semantic-based topological representation was defined based in the context of building fire safety. In the semantic model proposed by Meijers et al (2005) [5], for building evacuation simulation in extreme scenarios, polygons was used as the smallest unit which were given meaning with respect to their role and allowing people to walk around.

Unrelated to the field of simulation of human behavior, other studies directed the development of semantic enriched BIM models for a comprehensive representation of the historical artifact as (Simeone et al, 2014) [6], (Carrara et al, 2009) [7] Knowledge Representation Model for Cross-Disciplinary Building Design, both ontology-based.

Some studies focused on integrating BIM and gaming technology for familiarizing professionals with their new work environment by the means of simulation (Merschbrock et al 2014) [8]. Boeykens 2011, utilized of BIM resources linked to game engines to aid in the creation of digital, historical reconstructions of architectural projects. [9] In essence all those examples faces with the same struggles, how to elaborate a model able to support different aspects for evaluation practice. Still Boeykens adds that modeling qualitative geometry for use in regular visualization already poses an elaborate effort, preparing models for different uses is even more complex. In practice it is unfeasible to create different models independently from each other, so a balance has to be found between the desired usage and the available model data. [9]
Promising directions of semantically enriched BIM applications, knowledge-based models and game engine linked to BIM in the AEC industry is to facilitate various rule checking and simulations for evaluating building designs in the earlier phases of a project [10]. Those experiences provide subsidies to reinforce the model proposed in this paper.

1.2 Methodology

Existing methods have been using as systems of grids (Breslav, 2013) [11], voxels (Goldstein, 2014) [12], and cells (Tan et al, 2014) [13], for space discretization as calculation units. On the method presented in this paper the calculation unit is called “activity zones”. Those zones were defined according the designer criteria, considering the architectural project’s program, sectoring of uses, flowcharts, organization charts and more subjectively, the intention of sense of place ascribed to spaces. Unlike those studies previously mentioned, that basically used these units to calculate path finding or quantity of energy stored, the activity zones are divisions to assess the space qualitatively. The zones can be activated in different levels of resolution as required for the semantic definition.

The Sammy Ofer Heart Building at Sorasky Tel Aviv Medical Center was chosen as a relevant case study. The tower building, designed by Sharon Architects & Ranni Ziss Architects, was constructed in 2008-2011 and consists of 55,000 sq.m including 13 medical floors of 3,100 sq.m. per floor and 4 underground parking floors designed to serve as an emergency hospital for 650 patients.

To define the Zones Mechanism of the hospital internal ward, the following sequence of steps was established: first dividing the plan in zones according to activities that are addressed to be performed on it, then subdividing large areas in smaller units, establishing more detailed features of each space. Less generalized and discretizing those large areas with a huge range of different aspects contemplated. So it was intended in order to calculate it, which suppose to consult a large amount of data concerned to each small corner, all the specificities that is up to them.

In the Open Space – zone 5 (see Fig. 1) for example, the vestibules close to room’s entrances are characterized by different ceiling heights, specific materials on floors, finishing of walls and different intensity of lighting. It provides to users particular sensations that certainly should be considered in the evaluation process. Some aspects as noise can induce users to choose different paths to find their final destination. For instance when a visitor hear a supposed private meeting between doctors in front of the elevator and according to his personal traits choose not “disturbing” and deviate his route.

The criteria established to define the boundaries of zones is: by static physical elements as walls, finishes of floors and height of ceilings; flexible elements such as curtains and doors, as well as non-physical like flows (in crossing areas close to entrances) or areas of permanence (around patient beds). The roles of the zones are mainly three:

a) Detection of objects, actors and activities as soon as their respective positions;
b) Recognize objects ID, actors profile and the kind of activity performed;
c) Report possible affordances correspondent to each zone, and consequently define a semantic to the space.

Spatial character, data maps (noise, temperature, smell, density) and human activities must be considered in the representation of future buildings, in order to generate outputs about perception or social impacts derivate from built environment. Those are some of the aspects that conducted the configuration of the zones applied in this study. The first macro level is delimited following the activities affordances (Table 1):

<table>
<thead>
<tr>
<th>Zone</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>Central Core</td>
</tr>
<tr>
<td>Zone 2</td>
<td>Support</td>
</tr>
<tr>
<td>Zone 3</td>
<td>Administration</td>
</tr>
<tr>
<td>Zone 4</td>
<td>Clinical</td>
</tr>
<tr>
<td>Zone 5</td>
<td>Open Space</td>
</tr>
<tr>
<td>Zone 6</td>
<td>Escape Stairs</td>
</tr>
</tbody>
</table>

Table 1. Zones division and activity affordances.

Fig. 1. Zones and subzones division plan according to activity’s affordance.

Fig. 2. Zone 4 “Clinic”, divided in 4 sub-zones.
The definition of semantic of spaces in virtual built environments oriented to BIM implementation

Different levels were created to give the possibility to activate them according to the activity performed. It enables a subzone to have concurrent semantics in such divisions independently as the formal division of the space defined by the architectural plan. The level of activity zones serves as background of the Data Maps of: density, privacy, visibility, control, light, noise or smell. The higher level provides to the model a higher specific affordance constraint. The zones were divided into hierarchical levels, forming a tree structure, activated according to the hospital operation.

Zone 4 (fig. 1) can be divided in sub-zones (fig. 2), in which functions can be: patient rooms (C.1 and C.4), Isolation units (C.2) and intermediate unit (C.3). Those affordances are options of possible uses for those spaces, but it will be not only defined just when actors indeed use them. We can say that if zone C.1 is occupied by inpatients, it is considered a patient room, but in the other hand if no activity is detected, only occupied by equipment it could be considered merely a storage area.

Suppose that the more specialized the space is designed, less affordances options it will manifest. This is applicable for example to operating rooms, kitchens, laboratories, toilets, air conditioning installations and boiler room. Space can offer a list of possible uses, and also impose rules of affordances. A room by its physical constrains can afford being a patient room, clinic, infected room but not kitchen.

The rules of Space in this case are to define it’s affordance based on environmental conditions, physical settings and user’s profile. A direct consequence of this is the
influence on user’s reaction. If we suppose that space rule says that it is a *meeting room*, or **staff** area, users like visitors or patients cannot enter. Once they are already in the space, rules can invite them to retreat the place to enable continue “only staff” activity.

![Architectural layout and activity zones of “patient rooms”](image)

**Fig. 4.** Architectural layout and activity zones of “patient rooms”.

Figure 4 consist the subzones applied to patient rooms. The dashed lines represent flexible boundaries between zones. They may be tangible, in the case of curtains or conceptual, because of the sensation they cause. The flexible division is much more complex than the division by static physical barriers. We see in the example of the curtains that they can segment the space from the visibility aspect but not from the point of view of noise. This kind of observation is important to be considered when a patient should be helped in a hallway or in a room with more patients. The building design should provide the User an experience the least unpleasant as possible.

The Zones and Sub-Zones levels can be activated according to the data queried during the simulation. The data can be divided in *static*, which is pre-computed, and *dynamic*, generated during the simulation, some consequences of the activities itself (as noise or smells generated by other actors/activities). Also affordances can be dynamic. One room can be pre-defined as affordable for checking patient but once during the activity the room is not ready cleaned, it cannot afford the use.
The user’s perception of all those characteristics of the space will let them to behave according to their preferences. Users will consider a space inviting, cold, private, depressive, cozy or comfortable enough or not to perform their activities. This prediction is a fundamental output that this model can provide to designers, differently of what happens with other conventional models.

But in terms of simulation how can BIM model actuate smartly to represent this animated status triggered by users? The model can offer other kind of data (not only geometric, topologic or related to materials). A Virtual Sensitive Environment (VSE) model can act actively being aware of the phenomena that take place within it. For example, if a building is aware of how many people are in an auditory, this data can aid in the simulation of acoustic calculation. If the building is aware of objects presence (as computers or other equipment producer of heat) in a lab, it can help on thermal calculation. The property of awareness is an important aspect to generate inputs to the simulation.

Space by means of awareness has the ability to answer which kind of activities are being performed in a room, by whom and where. The space can be sensitive (detect) of environmental conditions as: temperature, noise and smell. This data can be reported to users, as they demand this data to supply their personal preferences. To experiment the effectiveness of this feature of space, some study cases were developed.

On a wider scale, the environmental model is combined with a behavioral model. In this approach the intelligence is distributed in actors, activities and spaces. Each one of these 3 parts of the tuple are repositories of different type of information. Studies have being added the information on virtual users (Agent-Based models), and in this approach the smartness is enhanced in the space (Virtual Sensitive Environment). One of the technical reasons of increasing the data of the building model is not to overload the data correspondent to the users. This enables to the system a better management of the databases. In this case, is given to the space sensitivity qualities that make it

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**Fig. 5.** Input data of the semantic model in the context of Human Behavior Simulation.
smarter than conventional representation. It is noteworthy that this study is experimental and seeks to verify the effectiveness of the hypothesis of increasing the level of smartness space.

The environmental model can achieve gradual levels of autonomy in semantic decisions; in essence increase level of smartness depending on context. Some physical limitation as blocked passages, locked doors, reflecting pools, height differences or voids imposes itself limitation of affordances. In parallel, at the moment the model is embedded with such added knowledge, the environment becomes active on influencing on human behavior. Space can pull coefficients values of noise, light or density and stipulate conditional rules. Ex: If density<3, then room C.1.5 affords=clinic, sleeping, visiting.

In a room multiple activities can happen simultaneously. Supposing that one activity zone C.1.5.2.3 is activated, in the moment that the space detects another activity, a higher level of the subzones are powered: C.1.5.2.3.1 and C.1.5.2.3.2. In the same room (fig. 6), despite being among the same four walls, it might experience two different semantics: examination room and visiting room. If the semantics are conflictive, affordance rules will be consulted in order to decide, according to the compatibility, which semantic will prevail. This means that one of the activities must be aborted.

If in another case, the open area is used as a corridor and suddenly another activity is triggered, like patient check, the subzone is activated and the same area can support different semantic approaches. If no conflict is detected, the activities can continue. Users are represented as: D1 (Doctor), P1 (Patient 1), P2 (Patient 2), and V1 and V2 (visitors) respectively.

![Activity’s affordance rules](image)

Fig. 6. Rules to define activity’s affordances in zones mechanism’s theoretical frame.
1.3 Case study: hospital patient rooms

To validate the usefulness of adding knowledge to BIM and the quality of awareness of space were developed 3 case studies. A BIM model of a Health Care Unit was developed, considering all parameters related to relevant geometries. It was simplified, avoiding a high level of representation detailing furniture, sanitary equipment and doorframes in order to reduce the file size. The BIM model was divided in Zones according to the theoretical frame.

By the means of tags, Autodesk Revit can attribute parameters as shown in Fig.7, in properties menu, at the left side the “semantic affordances”. The properties menu is filled with this data provided by the designer, with the previously stipulated possible uses (affordances). This selector is used than in the simulation. Usually BIM model data generated in Revit can be exported to databases for updating and later external data imported and merged into the model, using Revit DB link tool.

In this case the model was divided by the zones definition and the file is exported to .fbx, imported-exported to 3D Studio Max, and finally imported to the game engine, without the need of extracting the database separately of the 3D file. Unity 3D was elected as the most suitable software to this experimentation due to the facility of manipulating BIM models created in Autodesk Revit. The game engine relies mostly on import through the FBX file format, analogous to other, similar game engines. Unity provides a useful API that is accessible through C# scripts and JavaScript for basic game engine functionality [14].

Game engines are composed of two different parts: a scripting interface, where behaviors of agents and objects are structured and computed (behavioral model), and a 3D environmental model, where these behaviors are actually visualized [15].

Unity enables the access to the BIM database because after the import of the fbx file, all building elements modeled in Revit are available as separated objects, identified by the original object ID. As this ID description is identified in the virtual world, several scripts allow the connection between Unity and Revit elements.

Fig. 7. Properties menu options of semantics affordance to each sub-zone. In order to enrich the representation with not-geometrical data (i.e. activity zone, users allowed to enter, data map status, etc.).
In Unity 3D is possible to code the rules of spaces and actor’s behaviors. Is possible to visualize artificially how avatars behave in the virtual model following the rules and restrictions imposed in the script. Affordances rules were assigned to the space reflecting natural constraints that occur in the functioning of healthcare facilities.

In the case studies, were elaborated hypothetical narratives situations, based on real facts of hospital dynamics often found on those environments. Events commonly observed as patient visits, medical care, medicine distribution, equipment flow, emergency care, waiting for treatment were inspirations for the creation of these cases:

- Case nº1. In this scenario when the zone detects that there’s a bed in the corridor, automatically changes it’s semantics as “patient room”. It evidences the ability of space to change the semantic according to awareness of objects presence. Specialized rooms as bathrooms and kitchens has specific installation and objects that independently of activities being performed or not can have a semantic defined, only by the presence of those elements. We can consider those zones more rigid, with a few semantic possibilities (affordances).

In the piece of code is defined the rule of the void (a Bounding Box created in green). The fbx. file contains the properties of the BIM model menu: activity zones and semantic affordances, that once opened in Unity these parameters are linked to the rules. This simulates the semantic shift from “hallway” (bed detected=false) to “medical place” (bed detected=true).

![Fig. 8. Unity 3D view: a bed is detected in the “hallway”.

Program set of code rules that define it then as “medical place”:](image)
Void OnTriggerStay(Collider other) {
    if (Bed == true) {
        Medical_Place = true;
        HallWay = false;
    }
    if (Bed == false) {
        Medical_Place = false;
        HallWay = true
    }
}

- Case nº2. During a medical procedure, the visitor wants to approach to patient bed, and the B. Box (representing the sub-zone) detects it’s presence – visitor, but the semantic of the space does not afford the semantic “visiting room”, so it remains as “medical place”. In this situation the visitor is forced to detour and find another way. It proves the ability of the space to detect **users presence** at the space. This property can identify the “id” of the actor and recognize if it is a Doctor, Nurse or Visitor. In another situation, visitors can pass through the corridor if the semantic of the zone is “day room”. At the same time the space rules can set affordances to indicate if users are allowed to use or pass through zones, rules can impose in case of infected room, constrains meaning that the visitor’s entrance is forbidden. The space can detect and prevent when an “intruder” trying to invade impropriated areas. For instance, a door can include knowledge about the users already inside the room and decide if the approaching user is allowed to enter or not. [5]

![Figure 9](image_url)  
**Fig. 9.** Unity 3D view: visitor cannot access infected room (zone c.2.2.1).

Program set of code rules that define that zone access of “infected room” If equipped is detected, than the door opens and the actor can enter.
if (Equippeddetected == true)
    if (InfectedDoor.transform.localEulerAngles.y < 180)
        InfectedDoor.transform.Rotate (0, 0, Time.deltaTime * 30);
    else if (InfectedDoor.transform.localEulerAngles.y > 260)
        InfectedDoor.transform.Rotate (0, 0, Time.deltaTime * 30);
if (Equippeddetected == false) {
    if (InfectedDoor.transform.eulerAngles.y < 0) {
        InfectedDoor.transform.Rotate (0, 0, -Time.deltaTime * 60);
    } else if (InfectedDoor.transform.eulerAngles.y > 90) {
        InfectedDoor.transform.Rotate (0, 0, -Time.deltaTime * 60);
    }
}

- Case nº3. The zone detects doctor and nurse starting a patient check. The action is only triggered when all actors arrive at the zone. Once space detects all actors, the action can start. If the medical procedure constrains does not allow the presence of visitors, therefore should immediately leave the area so the action can be continued. It shows how space can detect activities and how to structure this mechanism; target boxes are positioned close to patient bed. The system attracts avatars to them. In the script a condition is defined: only start patient check if all actors required achieved their target positions, and visitors presence is not detected in the room.

Fig. 10. Doctor and Nurse already positioned to start “patient check”.

Piece of code that indicates the activity can just start once Patient 01, Doctor and Head Nurse are present and visitor abandoned the room:
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```csharp
// Update is called once per frame
void Update () {
    if (EventManager.PatientCheckGlobal == true &&
        Patient01 == true && Doctor == true && HNurse ==
        true && Visitor == false) {
        PatientCheck = true;
        PatientCheckDetect = true;
    } else {
        PatientCheck = false;
        PatientCheckDetect = false;
    }
}
```

Assuming the ability of the Space to be aware of those three components of Human Behavior Simulation (objects, actors and activities) we suppose that the space can report if there is a presence of person, his activity status (sleeping, busy, shower, being checked) and position (close to door or patient bed).

The building model once has the awareness property can be considered a “Virtual Sensitive Environment” (VSE). The intelligence is manifested in the building model (VSE) as happens in virtual users (VU), assigning more smartness to the environment. This is the guideline to achieve the subject proposed in this study.

1.4 Conclusion and Future Works

Once the simulation is concluded, the outcome provides the final semantic of the space. This is what will define the semantic of the spaces in the BIM model, which is the final use. In the Revit file, the zones are related to tags and we intend to update the tags semantic definition automatically. Now the system allows just a top-down control of possible affordances, but once the system will be automated, a bottom-up synchronous definition could be activated. The building’s ergonomic and environmental conditions affect human behavior as their interpretations of each space.

The aim of simulation is to evaluate how the building will be perceived, its impact on social relationships and how all those aspects combined affects the use. For future research we recommend the automation of insertion of dynamic data in the BIM model, as well as consideration of more complexities involving in human occupation of built environments.

The results of the evaluation depend greatly on the evaluator and the input criteria. Design performance evaluation consists of hard and soft criteria. Hard criteria are quantitative, measurable performances, such as thermal comfort, structural stability and cost. Soft criteria, on the other hand, are typically qualitative, based on subjective perceptions, such as aesthetics, social, psychological, and political “fit”, and therefore difficult to measure. [16].

In any case, the evaluation criteria can be focused to identify the appropriate semantic in the model. For example, as an output of the simulation it was found that many people are crowded in front of the nurse station. It has been seen that it is better not to give affordance of “patient room” in this part of the corridor. The consequence
is that the design will not include an additional bed in this area, since the space is less appropriate for this function and cannot provide reasonable comfort to a patient.

The next step is to create this sensitive environment in BIM, as it happens in other approaches as temperature control for example. It is possible to insert sensors in BIM, but it is important to provide content-rich information. To support facility management or evaluation of building performance, the system requires relationships between sensors and building elements as well as function of the space (office or patient room). To support rich information query of building conditions considering human behavior, is suggested to extract the information generated in simulations as type of activity being performed and recognition of users’ ID, as soon as their personal traits (in Unity 3D in our case).

Several rule-checking systems rely on IFC building models as input. The HITOS project is an example of using rules addressing accessibility checking [17]. They mostly define the requirements from a database based on legislation and universal conventions of design. Through this system proposed on this paper is possible to feed this database based on users experience and then run such inference engines. Rules can be created based on the observation of human behavior in other types of buildings. This data can feed an inference engine system that offers suitable outputs for each type of project. Schools, airports or shopping centers can also use this mechanism to feed the rule system for selection of semantics.

The literature shows that Building Information Modeling has potential to simulate various stages of the construction process, however, most of the existing efforts largely rely on human input or offer knowledge-based/semi-automated implementation. Further automation of the tool and better visualization are new options to be explored. [18]

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References

Closing the loop
From analysis to transformation within BIM

Stefan Krakhofer¹
¹ City University of Hong Kong
stefankrakhofer@gmail.com

Abstract. The shift from traditional CAD to BIM has created a significant potential to embed optimization processes in many stages of the design. The presented research is situated in the early design stage of inception and concept, focusing on analysis-driven-form-finding during the integrated design approach within a BIM environment. A custom analysis framework, has been developed and linked to a visual programming environment that allows the exchange of data with the parametric components of a BIM environment. The developed workflow and sequential split of functionalities enables a shared design environment for multiple experts and the design-team. The environment is intended to close the loop from analysis to parametric modeling in order to generate and evaluate building designs against performance criteria, with the aim to expedite the design decision process. The prototype has been presented to participants of the Deep-Space Cluster at SmartGeometry 2014.

Keywords: Algorithmic Design, Parametric Design, Parametric Analysis, Building Information Modeling, Design Automation.

1 Introduction

Since the adoption of computers in the architecture, engineering and construction (AEC) industry, the mode of practice has experienced a paradigm shift, transforming from post-rationalization, and pre-rationalization to embedded rationality.

1.1 Post-Rational Approach

In the post-rational workflow, the building is design by the architect according to his or her best knowledge. Afterwards the building’s performance is analyzed and evaluated, and improvements with minimum visual impact to the original design are recommended.
1.2 Pre-Rational Approach

In the pre-rational workflow, the building is design by the architect with a rational in mind that may address the structural system, the material selection, the overall architectural geometry [1], etc. During the design process the design is developed within the adopted constraints, potentially resulting in an optimal solution.

1.3 Embedded-Rational Approach

The embedded rational workflow relies heavily on computation due to the necessity of combining performance assessment and form finding in a single iterative system [2]. Aishargues that the embedded rational approach is "the most appropriate to truly open ended design optimization" [3]. Despite the potential benefits, the pure embedded rational workflow seems at this point only rarely operational, when taking into account the general design practice.

1.4 Integrated Design Approach

As an alternative to the pure computational embedded rationalization approach, the integrated design approach presents a collaborative method that emphasizes on holistic design. The focus of this method is on well-organized and well-managed design data and a collaborative environment. In the past ten plus years this approach has gained momentum with the transition from traditional Computer Aided Design (CAD) to virtual building design titled as Building Information Modeling (BIM). The shift from traditional CAD to BIM has created a significant potential to embed optimization processes in many stages of the design.

The presented research is situated in the early design stage of inception and concept, focusing on analysis-driven-form-finding during the integrated design approach within the BIM environment, Autodesk Revit. From a sustainable point of view, the early design stage contains the most potential to achieve an increase in building quality, performance and cost savings in the long run. Targeting these benefits, the integrated design approach emphasizes on early information sharing in order to achieve the desired outcome fast, efficiently and effectively [4]. The integrated design approach is affecting the design process as shown in figure 1, by shifting the main body of work from the center towards the beginning of the process.

Due to the importance of effective and efficient information sharing, the core of the presented research is on defining the transition points between various project partners and specialist in respect of form finding for performance enhancement. In respond, the first prototype in form of a custom analysis framework has been developed and linked to a visual programming environment that allows the exchange of data with the parametric components of a BIM environment. The developed workflow and sequential split of functionalities enables a shared design environment for potentially multiple experts and design-teams. The developed environment is intended to close the loop from analysis to transforming parametric models in order to
generate and evaluate building designs against performance criteria, with the aim to expedite the design decision process.

![Design approach and effect comparison. [4]](image)

**1.5 Design Equalizer – Task Separation**

During the analysis of workflow and best practice, it has been noted that architecture design projects rarely repeat and hardly their processes either. Depending on the nature of the project, contextual variables, such as design team, location, budget, client, etc., affect the sequential and weighted priority of those variables. Awareness of this circumstance allows the comparison of the design strategy to functionality of tuning an (design) equalizer where each variable can be tuned up or down depending on their importance for the present project. Informed by the design equalizer’s realization, the current project has classified the variables into separate task-flows where necessary. Within the BIM environment, these tasks are parametric modeling, analysis and linking them up in a loose relationship that allows relocating attention depending on the project needs.

**1.6 Analysis Framework**

The custom developed analysis framework’s ray-tracing algorithm and geometry handler have been optimized for performance to potentially enable an iterative
optimization loop. The kernel of this framework is a computational logic built on top of the lightweight spatial structure of a voxel definition. The aim of this framework is the rapid development of analysis algorithms that evaluate virtual models, visualizes concerns and opportunities, and enables a morphological responds within the BIM environment. Multiple criteria are identified and for each of these criteria, custom algorithms have been developed such as proximity, visibility, sky-factor, solar exposure, overshadowing, etc. The multidimensional voxel space enables to execute the algorithms simultaneously in order to create a composite picture. This allows the project to further develop into a multi criteria optimization framework.

The presented paper demonstrates on one case study the successful link of the developed analytical tools with the parametrically defined geometry values defined in the design models of the BIM environment.

2 Research Background

The creative relationship between designers and computers has been vibrant since the very beginning with Direct Manipulation 1963, followed by End-User Programming 1980, Visual Programming 1988, Generative Components 2006, Model-Based-Programming 2009, and Design Script 2011. The trend of engaging with the computer as a design tool has been constantly raising up and current development projecting a tremendous impact on the architectural practice.

2.1 Design Stages

The architectural design and construction process has been organized by RIBA since 1963 into the “RIBA Plan of Work” [5] that presents a publicly available, standardized framework. The aim has been, to explicitly present the architectural process with its stages and responsibilities, reflecting the best practice as well as the underlying managerial structure.

In recent years the conventional plan of work has been challenged due to the increased demand for rapid decision-making in the early project phase. New technologies and processes, such as BIM have disrupted the AECO industry due to its integrated design approach [6] that suggests a Lean BIM process [7] towards better performing buildings. The integrated approach implies that more information has to be processed early on in the design stage. This puts pressure not only on the design team, but also challenges the “Plan of Work” in respect of fee structure, contracts and responsibilities. As a result the time needed for analysis, evaluation and transformation becomes critical, and therefore needs attention.

2.2 Workflow and Data Communication

“RIBA Plan of Work” provides a good overview about the workflow during the design process. However with the adoption of BIM and the integrated approach to design, the traditional plan of work has experienced mutations. Due to the increased
amount of data necessary for evaluation early on in the design, the method of communication has changed significantly. Two-dimensional snapshots of analysis results have been replaced by three-dimensional analysis results and they in turn are being replaced by four-dimensional simulation of analysis results. The new dimension will be the interactive and contextual analysis in real-time. From the perspective of exercisability, these changes have created a gap in the evaluation process. Tools provided by the major software vendors, such as Autodesk, Bentley or Graphisoft provide analysis functionality within their platform. There is however a barrier of accessing the result and using them to drive geometric transformation for form-finding. There is currently no commercial tool available to the industry that supports rapid analysis driven form finding.

2.3 Computational Design Tools

Software is generally designed to satisfy the conventional tasks of a specific user group. This software ideally provides a graphical user interface (GUI) to ease the use of its functionality. In creative industries, such as architecture, computer-aided design (CAD) systems present the software of choice to support conventional tasks. In recent years however, the complexity of tasks increased and non-standard became the new standard. The use of complex geometry or the need for a more efficient workflow has created a demand for a new kind of software and “computer programming to have more capabilities and freedom to explore design options”[9]. Nowadays, most CAD packages provide programming interfaces and organizations such as Smart Geometry are hosting workshops and conferences that focus on applying computing on real-life problems. Many websites and blogs emerged with user groups that share their experience, such as design-reform, Digital-Crafting, designplayground, etc. The tendency to improve design thinking and design support using computational tools, has become generally accepted and a vibrant area for design research.

Great attention is placed on the increase of functionality of off-the-shelf software that has provided some powerful tools to enable parametric modelling and analysis. Semi-open development platforms attached to CAD packages such as Generative Components, Grasshopper or Dynamo allow for advanced process thinking. Open source software development platforms such as processing.org have been adopted in parts to quickly explore computational algorithms and simulation ideas, but demand rather high programming skills.

The problem at hand is yet, that architects are generalists and lacking the specialist’s knowledge, and time to deal with new computational technologies. Traditional design and workflow pattern are challenged.

On the other hand a new niche market emerged that specializes in complex geometry, BIM, digital fabrication and other design related technologies. New genres of practices have been formed to aid the industry with their design processes and computational support systems. To name a few that have sprouted up in the last few years are Evolute, Case, sliderstudio, etc. that provide specialist know-how regarding technology, geometry, management and design. This trend shows the increasing gap between design practice and technological demand and risks a disjoint of design and
production. The presented research contributes to a possible resolution of this situation as discussed in the case study.

3 Research Method

The presented research is centered in the architectural design field and thus aims to balance qualitative, quantitative and experimental research methods that merge during the case study stage of the project as highlighted in Figure 2 [10]. The research focuses on practical and goal oriented exercisability that includes at its core the user as a qualitative variable. In an effort to support the user’s decision making process, correlative research methods as part of qualitative research have been adopted. Correlative research is applied on a quantitative level used during the process of defining the types and combinations of analyses and subsequently on defining the relationship between their variables evaluated by their effects.

![Fig. 2. A conceptual framework for research methods. [10]](image)

3.1 Literature Review

The transformation from the traditional design operation to computer aided design operation has been scrutinized. The historic development of integrating computational means in the design process has been studied. The current development in visual programming has been evaluated and special emphasis is placed on linking them to parametric components in building information models. Primary research materials are taken from online conference proceedings, journals, articles. The target audience for this research paper is applied computational design research. In section six, all referenced material is cited.
3.2 Application

The ultimate goal of the presented project is to develop a framework for self-aware parametric BIM components that adopt within a simulated environment to contribute collectively to improve the performance of the virtual building design. Building on top of the initial research stage of constructive diagrams [11], the current research stage aims to establish a prototype workflow to test the functionality and applicability during the design process. The current stage also tested the link between the parametric BIM component and analysis data to trigger transformation.

3.3 Synthesis

Following the previous research stages, the current stage has established a working prototype that links analysis and transformation and thus closes the loop between context and form. The term context is rectified due to the chosen analysis type of a solar exposure that changes based on the provided context model. The major contribution consist of a C# analysis framework based on ray-tracing that is access from Dynamo via Python. Dynamo allows linking the analysis results directly into a parametric component in Revit, as described in more detail below.

4 Case Study

The presented case study aims to contribute to the subject of analysis-driven-form-finding. In an attempt to demonstrate the framework’s capabilities an urban scale analysis, paired with a small scale shading device responding to solar exposure has been chosen.

4.1 Workflow

Analytical analysis is becoming a standard procedure during the design process in order to guide the design development toward a well-performing project. These analysis tend to generate colorful representations that in turn represent numerical values. Increasingly, these analysis functionalities are provided within the CAD/BIM package used by the architect as part of the integrated design approach. In order to be practical beneficial, the user has to be able to visualize the results, navigate and access the data, and use them as input for the next design iteration that improves the performance. Currently, there is however no off-the-shelf tool available to feed the analysis result directly back into the geometry.

The choice of developing an approach that links a building information model with an analysis algorithm via a visual programming interface lies in the necessity of being close to the tool of choice by the architect. The visual programming environment allows an expert analysis algorithm to access the model provided by the architect without affecting the architects behavior and design habits. In essence the architect would develop a parametric BIM family and defines the parameters to be
changed by the analysis. The analyst would run the analysis and the team would see
the BIM family adjusting. This provides a visual feedback and a numerical feedback
that helps the design team to refine and optimize their family until the visual and
numerical feedback from the analysis is acceptable.

4.2 Approach

In the following the operational sequence of the developed framework is
provided. The initial input is provided by the design team in form of a Revit massing
model that will be used as context for the solar exposure analysis. The massing model
is loaded into dynamo, and the bounding box of the model is extracted. Within the
bounding box the space will be subdivided into voxels that are scalable. The voxels
within the massing model will be eliminated to reduce the amount of computation
later on. The remaining voxels are saved as vertex list and visualized in the watch 3D
node inside Dynamo. At this point it is important to mention that all the heavy
computation is done in dynamo and only the results are exported to Revit due to
Dynamo’s powerful geometry library. In the next step the massing model will be
optimized, describing the geometry as a light weight vertex list. The site location
provides the solar position during the day and year that are extracted from the weather
files in form of a vertex list defining vectors. The ray tracing algorithm is developed
in C# and is accessed by a Python node inside Dynamo. The Ray tracing algorithms
uses the solar vertex-list, the voxel vertex-list and the massing model vertex-list as
input and returns a list of values that match the voxel vertex-list IDs. The analysis
output can be visualized via a watch2D node in Dynamo. In the following step the
voxel vertex list will be sorted according to the analysis values and linked to a slider-
bar. Operating the slider-bar will switch on or off the selected range of voxels linked
to the values. This step is visualized via watch3D node (Fig 3). At this stage the nodes
are not applied to a color range to match the values, but will be integrated in the
following version. Alternatively Revit’s AVF – Analysis Visualization Framework
was used to apply the color range to match equivalent analysis representations.
Finally, via dynamo the parametric Revit family is selected and its parameters are
extracted. The parameters are adjusted according to an upper and lower bound
transformation rule to avoid breaking the family. After the parameters are adjusted
each instant of the family is places in the designated position within Revit. For each
iteration, the families will be updated.

![Fig. 3. Dynamo Interface and Blue Analysis Grid on context model.](image-url)
4.3 Application

The framework has been applied to an urban analysis project in Hong Kong, in a small neighborhood called Sau Wah Fong in Wan Chai. Due to the site’s opportunity for pure pedestrianized street activity, the project team has investigated the potential to increase the zones for human comfort on street level. Due to the climatic circumstance in Hong Kong, the initial target was Solar Exposure or also called direct sun light. The goal was to provide shading for the street level during the hot and humid periods of the year. A light weight canopy is proposed that is covered with Chinese Lanterns’ like components.

The initial step was to define the site location and extract the solar positions from the weatherfile. As benchmark for the analysis, only the hottest day of the year was chosen and the exact sun vectors are extracted and stored in an excel file.

In parallel, the team has generated a 3D context model, based on the Hong Kong Digital Map. In order to simplify the complexity of the context model, a 1m grid approximation has been chosen.

Together with the Chinese Lantern Artist, the geometry of the shading device has been developed. Special attention was placed on the rationalization for the subsequent fabrication of the lanterns. The BIMer has set up an adaptive-component-generic (Fig.3) within Revit and focused on reducing the necessary geometry to a minimum. The parametric family is based on a box with three profiles, whereby the middle section is used for parametric transformation. The upper bound and lower bound transformation rule was set to strategically as normalized value between zero and one, along the edge length of the box. That way the family avoids a faulty state and failure.

The team has then identified a layer within the model that is located on an average Podium level of twelve meter. This level was chosen to receive the analysis values. The following steps to complete the analysis to transformation are already outlined in section 4.2 Approach.

5 Conclusion

The conducted research presents the second stage of a five stage research. The initial first stage was focusing on developing and applying the concept of Constructive Diagrams with a BIM environment. In this current second stage, the constructive
diagram approach was exercised and extended with parametric BIM families that transform according to values derived from a solar exposure analysis.

Three aspects of the second research stage have been developed, tested and evaluated. The first part of the project was the development of a light weight parametric BIM family that provides one parameter that responds to the analysis values. For this part it can be concluded that the standard best practice modeling method for parametric families can be kept. The only aspect to pay attention to is to constraint the degree of freedom for the parametric transformation. A lower and upper bound has to be identified in which the value can adjust. This definition has to be communicated to the second part of the project, the Dynamo link.

Dynamo provides a visual programming environment that is capable of operating stand alone as well as linked to Revit or Vasari. Within dynamo, the import, export, etc. structure is set up. The key elements within the Dynamo structure are the Family loader and the family's parameter loader. Currently there is no mean to inscribe the upper and lower bound definition within the family and thus has to be set manually inside Dynamo. The other key functionalities are the import of solar vectors and setting up the voxel space. Both are fairly straight forward. The main analysis functionality is written in C# in Visual Studio and accessed from Dynamo via a Python Node. This enables an optimized algorithm and also provides the flexibility to replace the algorithms easily without the need to access Revit or Dynamo. This clean split of tasks within this setup has been proven to be suitable for the dynamic design process.

The whole process operates rather smoothly within Dynamo. However, when writing geometry to Revit, the process slows down due to the number of used Revit family and its heavy nature. The geometry kernel of Dynamo seems more powerful and lightweight compared to the Revit geometry classes and thus operates on a higher speed. In this respect further research has to be conducted to better understand the bottleneck within Revit.

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Point clouds to BIM

Methods for building parts fitting in laser scan data

Christian Tonn and Oliver Bringmann
Kubit GmbH
{christian.tonn, oliver.bringmann}@kubit.de

Abstract. New construction within existing buildings requires documentation of the existing buildings, in a form that one is familiar with from new construction or architectural design. Laser scanning is a powerful tool to survey the built reality. It provides a replica of the existing building in the form of a point cloud. The difficulty is to analyse the resulting amounts of data that has been generated and being able to interpret it as a Building Information Model (BIM). This article proposes a new generic approach for pattern recognition of architectural objects. The procedure is introduced through the use of two examples - polygon fitting, which is important for the generation of new building element classes and wall detection. The second part describes how individual components can be automatically connected to consistent networks. BIM systems walls should be aligned, within predefined limits of accuracy, either perpendicular to or in line with each other.

Keywords: point cloud, BIM, pattern recognition, components, wall alignment.

1 Fully automated versus semi-automated pattern recognition

Obviously every user wants automatic and error free pattern recognition of components in point clouds. But in the real world of architecture, fully automated procedures come very quickly on their limits. The subsequent time required for fault detection and correction exceeds the initial advantage of the automated procedure. Workflows are required, that leave control with the user, but at the same time, significantly improve the manual modelling.

As has already been explained in [1], fully automated methods are inadequate in practice for the following reasons:

- Interference objects in point clouds such as furniture, panelling and room plants inhibit automated pattern recognition as they are not capable of being modelled or singled out in the target system.
- Real objects are not as abstract as they are modelled in the BIM system. Instead, in reality there are many more details (see Fig. 1) and characteristics than can currently be simulated in the computer.

Point clouds are partly incomplete because of shadows, which the computer should invent, to create a correct model.

Semi-automated procedures involving the user, have a clear advantage in this situation, because they can utilise the user's expertise and experience for modelling and pattern recognition as well as make the whole procedure more accurate and quicker than by just simply tracing over it manually.

2 Polygon Fitting

The task of 2D-polygon fitting is, after a very roughly estimate of the polygon to be defined, to determine its optimum location within the point cloud. The best degree of quality is when the sum of the distances of all polygon segments to the densest points in the point cloud is at a minimum. To enable a complex search (e.g. by using simulated annealing [3]), an extremely fast computable and at the same time a very clear measure of quality is introduced. Especially with many independent parameters, such as when fitting a polygon, efficiency becomes important.
Figure 2 shows an initial polygon (red), used as the starting position, over a section through the point cloud (black). Now polygon parameters are now optimised by using an iterative process. In this example, the parameter set consists of the point coordinates of the polygon corners. This set of parameters is varied in all possible combinations by an ever decreasing epsilon value. An error function calculates the measure of quality of the new parameter set and uses this new parameter set for the polygon, if its measure of quality is better (simulated annealing procedure). Here the main loop as pseudo code:

Repeat until the measure of quality is satisfactory.
   Select a parameter at random.
   Slightly modify the parameter.
   **Calculate the measure of quality.**
   Accept or reject parameter variation.

The main problem with this approach lies in the effort required for the calculation of the measure of quality, which must be determined many times, especially with a lot of parameters.
For this the following approach [4] is suggested:

1. The error function is smoothed out in a look-up image, in which the section through the point cloud is distance-transformed and filtered into a so called "Potential Profile" (see Fig. 3).
2. The polygon is divided equally by polygon segment points.
3. Now the smallest distance of each polygon segment point to the point cloud can be quickly determined. This is achieved by simply reading the pixel value in the "Potential Profile". The sum of these values read from the look up values results in the measure of quality for the current polygon fit.

Through this preliminary computation approach of the "Potential Profile" it is possible to very quickly optimise of the polygon fitting and to adapt the topologically and diagrammatically defined polygon to the point cloud.

Calculate the Potential Profile.
Repeat until the measure of quality is satisfactory.
    Select a parameter at random.
    Slightly modify the parameter.
    **Very quickly calculate the measure of quality.**
    Accept or reject the varied parameter.

3 Wall Fitting

In the current BIM system you must first select the wall type together with the appropriate wall thickness before creating a wall. Then select the precise start and end points of the wall axis.
When fitting the walls the information to wall type and wall thickness together with the correct wall axis should be derived from the point cloud. The problem to be solved is, with just two mouse clicks anywhere inside of the wall, to determine the position and type of the wall and insert the wall entity.

The procedure first reduces the three-dimensional point data of the floor level to be analysed to a grey scale image (floor plan point density image with threshold, see Fig. 4). It is assumed the wall is vertical and straight. The approximate height of the wall is also given. This allows the problem to be reduced to a 2D analysis. The relevant section of the image (see Fig. 6) is converted, by using a customised distance transformation, into a second image, which shows the shortest distance of each image point to the next densest point cloud cell (see Fig. 7).

In contrast to the previously discussed polygon fitting procedure to create the "Potential Profile", in this use case, a grey scale image (floor plan point density image with threshold) is converted in to the "Potential Profile". This approach also takes into account the point density information in the point cloud. The grey scale image is simply split into 8 luminous intensity segments, which in turn can be considered as a distance transformed black and white image. These 8 distance transformed images are then weighted again according to their original luminous intensity values and combined into a "Potential Profile".

Furthermore, the "Potential Profile" is split into two separate fields. The boundary is the initial line clicked by the user. Based on this border two separate fields are formed, an upper and a lower field, where the point cloud density images can be, independently of each other, converted into a "Potential Profile". Thereby one avoids the possibility that point cloud points on one side of the line initially clicked can influence the line fitting results of the opposite side.
These distance images allow a local minimisation of two parallel lines which can be performed extremely quickly. These lines represent the inner and outer surfaces of a straight, vertical standing wall.

![Diagram of wall fitting](image)

**Fig. 5. Diagram of wall fitting**

The three optimising parameters to be determined for this wall fitting function are:

1. the angle of rotation $\alpha$ of the wall axis to the initially clicked line,
2. the "upper" distance $d_1$ of the wall surface and
3. the "lower" distance $d_2$ of the wall surface to the rotated click line (see Fig. 5).

In contrast to a fully automated procedure the user can here additionally use corrective intervention, if the wrong line segment (e.g. of a window etc.) was found for the local optimum of the wall surface. After a first quick optimisations iteration, the user has the option to click on up to 4 correction points in the image, which will have a corrective effect on the start position of the two line segments. After entering a correction point a new optimisations iteration is carried out in order to adapt the inner and outer sides of the wall onto the point cloud.

![Wall fitting optimisation procedure](image)

**Fig. 6. The wall fitting optimisation procedure - find two parallel lines**
After the wall thickness information has been obtained, the user can select the appropriate wall type from the pre-sorted BIM catalogue of all wall types (see Fig. 8) and draw it, or the precise wall thickness measurement can be appropriately rounded to a meaningful value and continued to be used.

4 Align Walls

In the next step the fitted walls, all of which have precisely the measured values from the point cloud, will be adapted to meet the requirements of a generalised BIM model [2]. These requirements include: perpendicularity, parallelism, continuous alignment with changing wall thicknesses and automated trimming/extending of wall segments (see Fig. 9). The core problem is to form the optimal wall disjoint clusters. Within a cluster, the requirements are enforced to minimise the deviation from the point cloud.
Fig. 9. Wall segments of a floor plan before and after the "Align Walls" function. The walls in a reference system are aligned perpendicular to, parallel and in-line with each other.

Fig. 10. Align Walls in PointSense for Revit: The automatically detected reference systems are shown in colour.

The algorithm for this purpose can be roughly divided into three steps, which are processed in sequence (see fig. 11):

1. **Rotate** – Each wall segment is rotated so that it lies within its "maximum deviation for reference systems", and that parallel clusters are created. A reference system consists of a main direction angle and an increment angle (usually 90°) in the XY ground plane. Such a reference system will be assigned to each of the walls (see Fig. 10).

2. **Axial alignment** – It is checked to see whether all parallel walls within their "maximum deviation for wall axis alignment" can be moved onto a common axis. This axis can lie on either the inside or the outside of the wall. The side having the smallest deviation from the fitted start position of the wall is chosen. Once again clusters are formed for creating the wall axes.
3. **Wall Trimming** – Within a specified search radius, all the ends of the wall segments are automatically trimmed or extended to create a closed floor plan.

![Fig. 11. The three steps of the algorithm](image)

Below the algorithm is semi-formally explained in more detail:

**Rotate**

1. The total number of walls is $W = \{w\ldots\}$
2. Generate user-defined reference systems $URS = \{urs\ldots\}$ by the combining of:
   a. If applicable: a single one for North (with main direction angle $0^\circ$)
   b. If applicable: for each reference direction manually created by the user
   There are so many clusters formed $C = \{c\ldots\}$, as there are entries in the $URS$
   Each cluster has access to its main direction $c.direction$
3. Try to assign all walls $w$, to the best fitting cluster $c$, i.e.
   $w$ is an element of $c$, precisely for all $c'$ ($c'$ not equal to $c$) where:
   \[
   \text{angle}(w.direction, c.direction + n \times \text{increment angle}) < \\
   \text{angle}(w.direction, c'.direction + n \times \text{increment angle})
   \]
   AND
   \[
   \text{angle}(w.direction, c.direction + n \times \text{direction angle}) < \text{angular tolerance}
   \]
   with natural number $n$
   with natural number $n$, that leads to a minimum angle
   *In exceptions some walls are left over.*
4. Generate, by automated clustering the possible directions $ARS = \{ars\ldots\}$ of the remaining walls $AW := W - \{\text{union of all walls } c\}$.
   There are minimum $0$ maximum $|AW|$ clusters $AC = \{ac\ldots\}$ formed.
5. Arrange all items from $AW$ in an ac analogous to rule (3) above.
6. $C := C + AC$
7. Rotate all walls of a cluster $c$ on the $c.direction n \times \text{increment angle}$
   with natural number $n$, that leads to a minimum angle
   *This should always be possible for a cluster.*
Axial Alignment
8. Create by automated clustering of possible axes $A = \{a \ldots\}$ for all subsets of parallel walls.
   The axis of an axially aligned cluster $fc$ is $fc.a$
9. Move all of the walls of a cluster $fc$ to $fc.a$, if permitted by the "maximum deviation for wall axis alignment", if more than one is applicable use the best one.
   This should always be possible for a cluster.

Wall Trimming
10. Now considered the wall segment ends. All nearby intersection points in the XY-plane are joined to neighbouring wall segments, which lie within the search radius. These intersections will be formed from the respective wall segment ends that are being considered.
11. Now the wall segment end is extended or shortened to its most remote intersection point with the adjoining segments.
12. The wall in the BIM system being used is defined by its mean centre line. Given that the wall axes are now topologically and geometrically correctly joined, the BIM system being used takes over the precise detailed modelling of the wall connections.

Below is described how "automated clustering" works, when used for both rotating and axial alignment. The described algorithm is adopted from the k-nearest neighbour algorithm [5]. The difference is, that in our case the number of clusters has to be computed to meet the user defined deviation parameters. First, the rotation should be considered:
1. Generate for each wall a separate reference system, that does not already exist for this main direction angle. At this point the error (i.e. the "maximum deviation for reference systems") should still be zero.
2. If the error is below the given tolerance, proceed as follows:
   a. Reduce the number of reference systems by the one whose sum of the squares of all of the errors results in the smallest increase in error. Also check all reference systems for possible "omission".
   b. Add the walls belonging to the removed reference system to the most suitable reference system still remaining.
   c. Calculate the resulting maximum error. If it exceeds the "maximum deviation for reference systems" immediately exit the loop or otherwise continue from "Point a."

In this way the necessary number of reference systems together with their main direction angle are automatically determined, to keep them within a certain maximum deviation.

The same procedure is employed for the automated clustering for axial alignment. Start with all of the walls in a single "axial alignment" group and then remove the group with the smallest error as long as you are still within the user-defined tolerance.
Fig. 12. “Align walls” - Coloured wall axes in a three storied building.

This approach obviously is an algorithm involving mean square time complexity in relation to the number of walls. The approach can be speeded up by heuristics, where the group of the walls to be examined has been previously subdivided. So, for example, in wall groups that could never be aligned with each other because of the set error tolerance. Because the individual calculation and error evaluation steps themselves are not so time consuming, the procedure can be applied to entire buildings in a reasonable amount of time. The three floors of the building shown (see Fig. 12) required around 3 seconds for the computation of "Align walls" on a commercially available desktop PC (Core i5-3570; 3.4 GHz).

5 Outlook

The "Fitting" method presented in the article should also be used for fitting other BIM component types. It is worth mentioning here that they would assist in the detection of
windows, doors and openings as well as beams and pipes. Similarly alignment, axial alignment and trimming should also be extended to other BIM component types. The semi-automated workflows presented, together with their own algorithms facilitate an efficient work process. There is a wide range of potential applications for pattern recognition in point clouds.

References

4D construction simulation model of MASP

Julian Kang, Gabriela Campagnol, Stephen Caffey and Mark Clayton

Texas A&M University
{Juliankang, campagnol, stephencaffey, mark-clayton} @tamu.edu

Abstract. Building Information Modeling (BIM) is an effective tool students can use to learn how building components work together to secure necessary structural stability in the course of construction. In Summer 2014, students enrolled in the BIM class at Texas A&M University created a 4-dimensional construction simulation model of the Museu de Arte de São Paulo (MASP) to understand how the entire building is sustained by two huge concrete beams connected with four external columns. For this class project, students analyzed the building system while creating a 3-dimensional model of the museum. They also came up with a construction sequence that would best maintain structural integrity of the building in the course of construction, and then produced a short animation video explaining the MASP construction process. This paper presents how the MASP project helped students learn a unique building system and its construction sequence.

Keywords: BIM, 4D Construction Simulation, MASP

1 BIM for Construction

According to the Smart Market Report on BIM released by McGraw Hill in 2009 [1], there is consensus in the construction industry, especially among contractors, that Building Information Modeling (BIM) helps to improve collective understanding of the design intent, which results in reduced conflicts and change orders during construction. McGraw Hill reported that BIM is most utilized by contractors for clash detection, spatial coordination, client engagement, shop fabrication, quantity takeoff, and 4D scheduling. Using BIM, general contractors can easily figure out the spatial relationship between building components, detect clashes between them, fix those clashes in advance, and then bring all sub-contractors in the same page for their roles and responsibilities in the course of construction. Four-dimensional visual representation of the construction sequence, which can be produced by assigning the start-date and end-date of each and every work package to associated building components, enables them to discuss constructability issues in advance, prevent reworks, keep their jobsite safe, and come up with plans for pre-fabricated modules [1, 2]. From academic investigations and tests, Riley [3], Akinci et al. [4], Guo [5], and Kang et al. [6] reported the advantages of 4-dimensional visual representation of the construction sequence in time-space conflict analysis and construction planning.
2 BIM Class for Construction

As BIM has been widely used in the construction industry, many contractors expect higher education institutions to teach students how to use BIM especially for construction management. [7] Many contractors are searching for students who understand how to create a building information model, how to detect clashes between building components, how to assist a project manager to remove those clashes during pre-coordination meetings, and if possible, how to produce a 4-dimensional construction simulation model that can be used for construability analysis or modularized construction planning. Understanding the competency that the construction industry is looking for, BIM has recently become one of the most popular topics among students in higher academic institutions. [8]

To provide what the construction industry and students are seeking, the Department of Construction Science at Texas A&M University offers a BIM class, which is basically designed to train students how to create a building information model, how to use BIM for clash detection and material takeoff, how to use BIM for presenting the construction sequence visually and analyzing constructability issues in advance, and eventually how to use BIM to enhance communication among project team members. In order to cover these activities that industry professionals do using BM, the BIM class teaches students 3 computer applications:

- BIM application for creating an object-based parametric 3-dimensional model of a building (BIM authoring application)
- BIM application for creating a federated 4-dimensional model which can be used for clash detection and presenting the construction sequence (BIM manipulating application)
- Computer application for creating a video clip.

Teaching these computer applications in one semester would be challenging for any instructor unless students are highly motivated. To get students motivated and trained effectively for the BIM skills that the construction industry is looking for, the BIM class at Texas A&M University uses the Goal Oriented Active Learning (GOAL) pedagogy, which is in essence about setting up the goal for students and help them actively pick up necessary knowledge while trying to accomplish the goal.

To set up the goal, the BIM class uses the semi-realistic construction project sponsored by construction firms. The goal of the BIM class is to develop the construction execution plan of the sponsor’s project and produce a video presenting their execution plan. Before each semester gets started, the instructor explores ongoing construction projects, analyzes student’s workloads associated with those projects, interviews the representatives of the construction firms to see if they are interested in sponsoring the class project. Once the project gets selected, the instructor collects 2-dimensional drawings of the project, determines the scope of the class project, and arranges the students’ field trip to the jobsite if possible. To get students excited and motivated about the class project, the instructor also arranges the sponsor’s visit to the BIM class, so that students have chances to meet the sponsor’s representatives. Once the BIM class starts, students are introduced to the nature of the
class project, for which the sponsor’s representatives visit the BIM class and help students understand what is depicted in the 2-dimensional drawings provided for the class project. At the end of the semester, once students have finished working on the class project and submitted their video to the instructor, the sponsor’s representatives are invited one more time to evaluate those videos using the rubric provided by the instructor. The instructor is basically asking the sponsor’s representatives to see if the video is explaining the construction execution plan effectively and logically using the 3-dimensional model and 4-dimensional construction simulation model.

To help students get engaged in active learning, the instructor uses various online resources including YouTube videos. Instead of explaining nuts of bolts of the BIM applications, the instructor explains the concept of creating the object-based building information model using parameters, and shows students the entire process of creating a building information model using a simple example. The instructor then asks students to create a 3-dimensional model of their dream house without considering any dimensional issues. While working on the first assignment, students are encouraged to use as many online resources as possible if they want to know a specific function of the BIM applications. Also students are encouraged what they have discovered with other students through social networking services including Facebook. The instructor invites some students to show the 3-dimensional model they have created to their peer students in class, which often encourages other students to get motivated and do more and better for the class project.

Coupled with the class project, the Goal Oriented Active Learning pedagogy provides students with a unique opportunity to pick up new knowledge with their own pace. Personalized learning method is about providing students with learning environments to meet the needs of individual learners. David Miliband [9], Minister of State for School Standards for the United Kingdom (U.K.), stated that “personalized learning is the way in which our best schools tailor education to ensure that every pupil achieves the highest standard possible”. Education leaders invited to the SIIA-ASCD-CCSSO Symposium on [Re]Design for Personalized Learning in 2010 jointly identified the following essential elements for personalized learning [10]:

1. Flexible, Anytime/Everywhere Learning
2. Redefine Teacher Role and Expand “Teacher”
3. Project-Based, Authentic Learning
4. Student Driven Learning Path
5. Mastery/Competency-Based Progression/Pace

The Goal Oriented Active Learning environment helps students learn how to use BIM applications at their comfortable speed while working on the class project. There are a huge amount of resources available on the Internet, and students are encouraged to take best advantage of them and pick up new knowledge at their comfortable speed. The instructor’s role is to set up the goal for students and monitor their progress in order to provide them with a competency-based progression model.

While working on the class project, students create a 3-dimensional building information model of the architectural components as well as mechanical, electrical, and plumbing (MEP) components. They also learn how to detect clashes between architectural components and MEP components of the building using BIM
applications. Students identify the work packages representing unit activities on the jobsite, determine how much time they need to allocate to execute these work packages, establish the sequential relationship between them, and develop a network diagram of these work packages, which helps students figure out the start-date and end-date of each and every work package they have in the network. Students then split the building information model into unit building components that can be matched with work packages they have identified. A 4-dimensional construction simulation model is created by assigning the start-date and end-date of these work packages to associated building components. Several BIM applications facilitate the production of the 4-dimensional construction simulation model, and enable users to time travel through the network of work packages. Students then develop a storyboard and script to get the idea as to how they want to present their construction project in the video using their 4-dimensional construction simulation model. Students also create animation clips supporting their storyboard, and produce a short video clip by stitching their animation clips together and adding narration using their script. The ultimate goal of this class project is to produce a video clip presenting the logical sequence of the construction process using BIM. To help students follow this challenging process, the entire class project is split into 10 smaller tasks as shown in the following list.

- Project 1 - Learn how to use a BIM application and create a building information model of their dream house.
- Project 2 - Create an architectural and structural model of the sponsor’s project.
- Project 3 - Create a mechanical, electrical, and plumbing (MEP) model of the sponsor’s project.
- Project 4 - Learn how to detect clashes and exercise this function using their own model.
- Project 5 - Identify work packages, develop a network diagram of these work packages, and figure out the start-date and end-date of each work package.
- Project 6 - Assign the start-date and end-date of these work packages to associated building components, and create a 4-dimensional construction model.
- Project 7 - Produce a poster presenting the work scope, logistic issues, construction sequence, and risk management issues of the project.
- Project 8 - Develop a storyboard and script presenting the execution plan for the sponsor’s construction project.
- Project 9 - Produce a draft short video presenting the construction execution plan.
- Project 10 - Produce a final video presenting the construction execution plan.

3 BIM Class Project: Museu de Arte de São Paulo (MASP)

In Summer 2014, the instructor of the BIM class at Texas A&M University decided to go with an unusual class project. In previous semesters, commercial buildings are
usually chosen for the class project because mechanical, electrical, and plumbing (MEP) components of those buildings are often collided with architectural and structural components, and those collisions are the good educational resources the instructor can use to teach students how to detect clashes and make proactive decisions to fix those problems during pre-construction coordination meetings. What was selected for Summer 2014 was the Museum of Art in Sao Paulo instead.

There are several reasons why the instructor selected the Museum project, which was already completed in 1968, over regular commercial building projects. First of all, the structural configuration of the building got the instructor’s attention. Unlike other commercial buildings, the MASP building is sustained by two huge concrete beams connected with four external columns, in order to leave the first floor open for the public. Lima stated that: “before construction of the museum, the site had been occupied by a small, sloping belvedere-park called Trianon Terrace, which included a Neoclassical composition of pergolas sitting on a large semi-buried ballroom built in 1916 and demolished in 1951. A constraint to building on this site was a city ordinance mandating continued public access to it and its street-level views” [11]. The MASP building designed by the Italian-Brazilian architect Lina Bo Bardi met this requirement by putting a semi-buried podium below the ground level, a plaza on the ground level, and an elevated exhibition hall on top of the plaza. To provide an open space at the plaza level, the entire exhibition hall is sustained by the 2 huge external concrete beams connected to 4 external columns. Coming up with a construction execution plan for a sustained exhibition hall would be a good challenge for construction science students.

The second reason that made the instructor to choose the MASP project was that the MASP building was relatively simple in terms of creating a 3-dimensional model. Since the summer BIM class runs only for 5 weeks, as opposed to 15 weeks in the regular semesters, the instructor was looking for a bit simple but still challenging project. The MASP building met the instructor’s expectation.

Once the MASP project was decided for the summer class project, the instructor started collecting 2-dimensional drawings. The instructor’s colleague who originally introduced this project helped to locate architects who designed the MASP building and collect 2-dimensional drawings from them. Since many drawings were not available, students were also suggested to use any pictures available over the Internet.

Students were give 1 week to create a 3-dimensional model of the MASP building. To help students better understand the building, a College of Architecture professor, who is familiar to the MASP, visited the BIM class and presented the history of the building, the configuration of the building, and the use of the building up to now. Although there was not enough drawings and information about the building, students managed to create a 3-dimensional model of the MASP building as shown in the Figure 1.
Students then moved on to the next step, and come up with a logical sequence of construction, for which they divided the entire project into about 50 action items, determined how much time they wanted to allocate for each action item, identified the relationship between action items, and then developed a network among those action items. Figure 2 shows the action items identified by a student who took the BIM class in Summer 2014.

With the use of construction schedule application, students identified the action items on the critical path and figured out the start-date and end-date of each action item. By assigning the start-date and end-date information to associated building components in the 3-dimensional model, students were able to create a 4-dimensional model that represents the sequence of construction. Figure 3 shows the 4-dimensional model presenting the construction sequence of the MASP.

Once the 4-dimensional model is produced, students now have a good understanding as to how they want to build the building. Before putting students into the process of creating animations and video, the instructor asked students to produce a poster that presents their construction execution plan. This activity was designed basically to allow student to develop some idea as to how they want to present their construction execution plan to the class project sponsor. Figure 4 shows one of the posters produced for the class project.
Fig. 2. Action items in terms of building the MASP

Fig. 3. Four-dimensional construction model presenting the construction sequence of the MASP project
Finally, the instructor asked students to come up with a storyboard and script they wanted to use to produce a video. After getting the script done, students produced several animation clips that support the script. Once multiple animation clips are brought to the video editing application, students aligned those video clips to be synchronized with the narration they recorded in advance using the script. After getting the first draft evaluated by their peers and the instructor in class, students produced the final video. Figure 5 shows the snapshot of the video produced for the class project.
Fig. 5. Snapshot of the video presenting the construction execution plan of the MASP project

4 Conclusion

The MASP project gave students enrolled in the BIM class at Texas A&M University a unique opportunity to study the building system of an elevated exhibit hall, which is sustained by the 2 big concrete beams. While creating a 3-dimensional information model, and 4-dimensional construction model of the MASP building, students learned how the structural integrity could be secured in the course of construction. The video production process gave students a chance to discuss how the construction execution plan can be better delivered through visual representation of a 4-dimensional construction simulation model.

Lack of drawings was one of the critical challenges that students had to deal with for the class project. Unlike other class projects, communication with the architectural firm that designed MASP building was also challenging. Students used then as many resources as they could find off the Websites, however it was challenging even to locate some pictures of the MASP building. Because many dimensions of building components are missing, students had to assume many dimensions, so the 3-dimensional model they created may not reflect the actual building correctly.

Still the configuration of the building with an elevated exhibit hall sustained by the beam is very attractive system, which can challenge students who want to learn how to develop a construction execution plan. Collecting additional information of the building, for example by visiting the building and taking additional pictures of the building or by collecting point clouds of the building using a 3-dimensional laser
scanner, may help the instructor to use the MASP project again for the BIM class project at Texas A&M University.

References

A BIM-compatible schema for architectural programming information

Ehsan Barekati, Mark J. Clayton and Wei Yan

Texas A&M University
{ehsan.barekati, mark-clayton, wyan}@tamu.edu

Abstract. Architectural programming, although a key part of AECFM processes, has not been well integrated into Building Information Modeling (BIM). Having access to architectural programming information throughout the lifecycle of a building can add value to design evaluation, facility management, renovation and extension. There is not currently a comprehensive and standard data model to store architectural programming information. Our research is producing a universal format for an architectural program of requirements (UFPOR) that can connect the architectural programming information to the IFC BIM schema. The result is a data model for architectural programming that is inherently interoperable with BIM standard schema. A graphical user interface facilitates data creation and manipulation. The schema and effectiveness of the bridging fields has been tested by entering the content of three two different architectural programming documents into the UFPOR database.

Keywords: BIM, Architectural Programming, Data Modelling, Interoperability, IFC.
A framework for speech-oriented CAD and BIM systems

José Luís Menegotto
Federal University of Rio de Janeiro
jlmenegotto@poll.ufrj.br

Abstract. This article discusses the development of a Speech Oriented Graphics Interface embedded in CAD and BIM software. The aim is to provide the means to work with complex 3D BIM models with minimal touch operations. We can cite the growing need for tools and user interfaces to assist designers in handling complex models, minimizing the risk of producing changes accidentally. In this area, the integration of a graphical database in BIM applications can be seen as an advantage over traditional CAD applications. However, we can note a difficulty in this integration, due to the need to maintain the constant levels of mental concentration required in order to effectively manage a larger inter-connected graphical database. Specifically in this area, voice interfaces can help by avoiding the need of "touch" to work with the 3D models, looking for improving its robustness and consistency. In addition, SR is used in order to reduce cognitive stress among the users, trying eliminating the need to memorize and remember commands, names and locations in GUI interfaces.

Keywords: Accessibility, Text to Speech, Speech Recognition, CAD-BIM.
Development of BIM performance measurement system for architectural design firms

Jihye Shin, Jungsik Choi and Inhan Kim
Kyung Hee University
{shj9025, junsikchoi, inkim}@khu.ac.kr

Abstract. Despite the effort of Korean government to vitalize BIM adoption in AEC industry, the domestic adoption of BIM is still in its initial step. Particular in design field where medium and small firms being the majority, shows lower level of BIM adoption. The primary reason for this can be considered as lacking of necessities caused by uncertain benefits of BIM. Therefore, it is time to develop the objectives, quantifiable and qualitative measurement system of BIM performances. The purpose of this study is to suggest the BIM Performance Measurement System for architectural design firms. In achieving this, the authors have developed Balanced Scorecard (BSC) and validated its appropriateness by questionnaire survey with experts and performing statistical analysis. This development can be contributed to the voluntary BIM adoption by visualizing the detailed benefit of BIM and to the improvement of enterprise competitiveness by facilitating management of design process and estimating future outcome.

Keywords: Building Information Modeling (BIM), BIM adoption, BIM benefit, Performance Measurement System (PMS), Balanced Scorecard (BSC), Critical Success Factors (CSF), Key Performance Indicators (KPI).
Facilitating fire and smoke simulation using Building Information Modeling

Chengde Wu, Saied Zarrinmehr, Mohammad Rahmani Asl and Mark J. Clayton
Texas A&M University
{chdwu22, szarinmehr, mrahmaniasl, dr.mjclayton} @gmail.com

Abstract. CFAST is a two-zone model which simulates fire growth and smoke transport. Manually modeling a building using CFAST user interface is a time consuming and error-prone process. In addition, the limitations in CFAST structure impede data transfer between CFAST and BIM (Building Information Modeling). In this research, we identified major limitations of CFAST, proposed solutions to the limitations, and developed a system for data interchange between BIM and CFAST. This greatly facilitated fire and smoke simulation. We further developed a visualization module to visualize the simulation results to overcome the problems when using SmokeView, an application developed by NIST (National Institute of Standards and Technology). A pilot test is conducted using this system. The simulation process was done in just a few minutes. This is expected to help architects to design buildings safer from building fires, and help students in learning building safety and fire related building codes.

Keywords: Fire simulation, building information modeling (BIM), CFAST, building fire evacuation
A semantic web approach for built heritage representation

Stefano Cursi¹, Davide Simeone¹ and Ilaria Toldo²

¹Sapienza University of Rome
{Stefano.cursi, davide.simeone}@uniroma1.it

²University of Southern California
toldo@usc.edu

Abstract. In a built heritage process, meant as a structured system of activities aimed at the investigation, preservation, and management of architectural heritage, any task accomplished by the several actors involved in it is deeply influenced by the way the knowledge is represented and shared. In the current heritage practice, knowledge representation and management have shown several limitations due to the difficulty of dealing with large amount of extremely heterogeneous data. On this basis, this research aims at extending semantic web approaches and technologies to architectural heritage knowledge management in order to provide an integrated and multidisciplinary representation of the artifact and of the knowledge necessary to support any decision or any intervention and management activity. To this purpose, an ontology-based system, representing the knowledge related to the artifact and its contexts, has been developed through the formalization of domain-specific entities and relationships between them.

Keywords: Built Heritage, Knowledge-based model, Ontology-based systems, Building Information Modeling, Semantic web technologies.
Fabrication and materiality
Digital stereotomy
The rejuvenation of stone masonry

Shayani Fernando, Rob Saunders and Simon Weir

University of Sydney
{Shayani.Fernando, Rob.Saunders, Simon.Weir}@sydney.edu.au

Abstract. This paper explores four factors contributing to the revival of stone masonry; aesthetics, externalities, representational tools and cutting technologies. The ongoing desirability of stone for architects and designers for aesthetic reasons; sustainability benefits of stone due to its potentially reducing hidden externalities of production and transportation; the development of representational tools in terms of advances in computer aided design, simulation, analysis and manufacturing; and advances in production technologies. This paper focuses on how digital technologies are making stone a viable material for architects and designers.

Keywords: Stereotomy, Stone, Voussoir Geometry, Arches, Robotics

1 Introduction

Product of nature, stone has been a building and sculpting material throughout human history. Michelangelo Buonarroti completed the colossal figure of David from a block of Carrara marble hewn from a quarry that had produced stone for two thousand years. Carrara marble is currently highly regarded as a classical natural stone. In fact current researchers in the region such as Carrara Robotics\(^1\) group developed robotic wire cutting based on prosthetic systems to carve into the stone. Wesley McGee director at the FABLAB in Taubman College University of Michigan wrote,

'Several researchers have tested applications for robotic wire sawing, but the capabilities of a robotically guided wire cutting operation to yield complex units in a finishes/semi finished state has not been studied extensively.' \(^1\)

The integration of visualisation systems with the flexibility and portability of industrial robotic manipulators could produce unparalleled efficiencies in stone masonry.

This paper explores the four main factors of the revival in stereotomy frequently referring to current designers who are developing stereotomic methods, principally,

\(^1\) Carrara Robotics based on Prosthetic systems: http://carrara-robotics.com/
http://vimeo.com/94076571

Giuseppe Fallacara, and also Philippe Block from the Block research group; the Hyperbody Research Group; and Professor Mark Burry work in the restoration and extension of the Basilica i Temple Expiatori de la Sagrada Família in Barcelona, Spain. Digital technologies are making stone an increasingly viable material for architects, this paper explores some advantages and limitations of working with stone.

2 The Aesthetics of Stone Cutting

The architectural preference for stone inevitably arose from stone’s ubiquitous existence; it is symbolic, elemental. Attached to this are the streams of cultural, psychological and ecological associations. It is durable, low maintenance, many are visually pleasing, it’s tactile and thermal qualities make it an enduringly desirable material. To an architect or sculptor’s eye, some visually attractive features of stone blocks are flaws, leaving them structurally fragile. Small pieces of stone, which will not be used structurally, can be flawed and therefore beautiful; large blocks that will carry heavy loads must be free from flaws. The vital task of identifying flawed and flawless stone begins in the quarry.

At the time of the Renaissance it was common for architects and sculptors to travel long distances to visit quarries, select the stone blocks, and make arrangements for their transport. Michelangelo always visited the quarries. For a facade project in Florence, after sketching the design, he selected a team of quarrymen, and travelled into the mountains, cut the immense slabs he chose, then delicately and slowly slide them many miles to the building site. The marble had to be of “good quality, white and beautiful, and without faults,” [2]

The statue of David, carved by Michelangelo from 1501-1504, from a large block of Carrara marble quarried forty years earlier in the Apuan Alps of northern Tuscany. Agostino di Duccio received the commission in the 1460s, roughed out the figure in the quarry to reduce the weight before transportation into Florence. Duccio abandoned this half cut stone and it remained in Florence until Michelangelo inherited it. Therefore the task that Michelangelo had in front of him was to find a figure sculpture inside a rough and irregular chunk of stone. Making the choices about how to cut back the stone is the art of stereotomy.

2.1 Stereotomy Defined

Stereotomy can be simply defined as the art of cutting solids. In relation to architectural construction, it is a set of geometric instructions and techniques of drawing and cutting blocks of stone for their assembly into complex structures. It has its origins as a French term combining two Greek words meaning „stereos“(solid) and „tomy“(cut).  

The earliest and most influential texts on cutting geometrical solids is Euclid’s 3rd Century BC texts. Although there is no unambiguous literary evidence for

2 Greek: ζηρέος (stereós) "solid" and ηομή (tomē) "cut "
3 Euclid: Greek (Εὐκλείδης) (Four Books of Conics by Euclid 300 BC)
theorizations of stereotomy between the Classical eras and seventeenth century France, Euclid’s works were likely to have been the core texts for the practice of stone masonry.

The French term has its origin in Philibert de L’Orme’s 1567 treatise on architecture. Although Fallacara does not suggest “a direct geometrical connection between Euclid and de L’Orme”, rather, that L’Orme had an interest in “Euclid’s work, considering it a very high digest of methodological rigor.” This conception of stereotomy is far more abstract than Michelangelo’s direct engagement with the stone and leads us into the problem of representation.

Sakarovitch in his paper, „Stereotomy, a multifaceted technique” describes stereotomy as “the art of drawing the shapes to be given to stones (and bricks) for future assembly” which also includes aspects of structural analysis.

3 Externalities

In economics an unpriced externality is any cost associated with the production of material that doesn’t have a direct financial impact for example the pollution of the environment. One of the key drives towards making the economy and the physical environment more sustainable is to turn unpriced externalities into priced externalities for example making manufacturers pay for their pollution. Considering the vast interconnectedness of manufacturing processes calculating all the externalities is exceedingly complex.

Professor Geoff Hammond and Craig Jones of the Sustainable Energy Research team (SERT) at the Department of Mechanical Engineering, University of Bath, UK created an inventory of the carbon and embodied energy found in common construction materials. They define embodied energy as the “total primary energy consumed (carbon released) over its life cycle...known as ‘Cradle- to-Grave’.”

<table>
<thead>
<tr>
<th>Materials</th>
<th>Embodied Energy Co-efficient EE-MJ/Kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stone</td>
<td>1.00</td>
</tr>
<tr>
<td>Concrete</td>
<td>1.39</td>
</tr>
<tr>
<td>Clay Bricks</td>
<td>3.00</td>
</tr>
<tr>
<td>Autoclaved aerated concrete blocks</td>
<td>3.50</td>
</tr>
<tr>
<td>Plasterboard</td>
<td>6.75</td>
</tr>
<tr>
<td>Timber</td>
<td>8.5</td>
</tr>
<tr>
<td>Glass</td>
<td>15.0</td>
</tr>
<tr>
<td>Steel</td>
<td>35.3</td>
</tr>
<tr>
<td>Plastic</td>
<td>80.50</td>
</tr>
<tr>
<td>Aluminium</td>
<td>218.00</td>
</tr>
</tbody>
</table>

Philibert de L’Orme is attributed with the origin of the stereotomic discipline. Original text: The First Volume on Architecture of Philibert De L’Orme, Paris, 1567
Table 1 reveals the low embodied energy of stone compared to other building materials which is an advantage in construction appeal. Sustainable building practice must include the costs of these negative externalities and produce an architecture that is truly cheaper, not just temporarily cheaper given the regulatory conditions.

Giuseppe Fallacara, also describes the current situation and renewed interest in stone in terms of its ecological and sustainable values:

>'The ecological qualities of stone are compelling: unparalleled durability, natural cooling, lack of pollution by toxic waste. The use of stone can reinforce the genius of the place by providing new buildings, however modern in form, that blend with the colour, texture, and materiality of the past'. [6]

4 Representational Tools

Stereotomy as a discipline of study in inherently, and increasingly, abstract. Through the nineteenth and twentieth centuries, it became largely an exercise in descriptive mathematics, with decreasing relevance to the material process of masonry. It is logical that the vast majority of highly skilled masons across the centuries were, or could have been, functionally illiterate and ignorant of mathematics. Their training was practical and physical. They gained their skills through intensive four-dimensional engagement, not through the study of two dimensional representations.

The usefulness of a book on stereotomy is inherently limited. A linear sequence of two dimensional representations is an inadequate manner of communicating wholly four dimensional problems. Perhaps responding to the limiting costs associated with printed illustrations, and an academic interest in mathematics, many stereotomy texts are works of applied mathematics. S. Edward Warren’s 1875 book, „Stereotomy - Problems in Stone Cutting”, contains a little over one hundred pages and only twenty six illustrations; the book no doubt would be more useful if these numbers were reversed. A.W. French and H.C. Ives” 1913 „Stereotomy”, a similar book of similar length, certainly improved the situation by including forty five illustrations, but the fundamental problem remained.

While the field of stereotomy languished in this half practical, half geometrical condition, the field of descriptive geometry, which academic stereometers pursued, ultimately contributed to the mathematical operations underlying digital modelling tools available today. These advances in mathematical representation have made stereotomic study available to people who do not have extensive knowledge of advanced geometry.

4.1 Gaudi and CAD

Antoni Gaudi based his geometry on hyperboloids, paraboloids, and hyperbolic paraboloids which closely resembles catenary curvature tracing the arch’s line of thrust. The geometrical problems of working with hyperboloids, paraboloids, and hyperbolic paraboloids are not covered in Euclid’s work. This means that most
masons were likely to have been unprepared to produce these shapes and that the graphical technique for the layout drawings was insufficient for the task. This may explain why Gaudi worked with models. As the work undertaken today is the effective reverse engineering of Gaudi’s models, a graphic technique was developed by his successors. Burry states,

’Such graphic techniques were the tools of the stereotomers of the past but the graphic technique for the intersection, for example between a sphere and cone, could not be adapted for the intersection between a circular and elliptical hyperboloid inclined differently with respect to the datum plane.’ [7]

Burry further explains that the benefits of computational models are the ready application of such tools to diverse aspects of the construction process: automated manufacture, calculation of volume and mass of the irregular shaped pieces, and the calculation of the centre of gravity to facilitate the correctly orientated hoisting of the heavy masonry pieces. It is a combination of a surface and solid modelling facility which is now making a significant impact on the working method. Solid modelling Computer Aided Design(CAD) tools can replicate the plaster model-makers methodology almost exactly, making them more likely to be used by architects investigating the potential for modern stereotomic practices. Computational modelling also enables an opportunity to work in a ‘parametric’ rather than ‘explicit’ environment. This is where the object can be described as a series of relationships to which dimensional values can be given later and changed at will. “This facility elevates the tool from working slavishly to a known intention to working more intuitively with the designer’s considerations.” [7] The models produced on the screen from these software programs can then be used to drive saws or mills directly and fashion either a model, a prototype, mould or finally the finished article.

5 Cutting Technologies

The return of stereotomy is largely due to the improvement of representational tools, with the application of these representational tools the material problems of the stone mason will become the pathway to revive the stalled tradition of stone architecture. As Fallacara states:

‘Once a slow and painstaking process of cutting each stone by hand, now stone masonry can proceed rapidly with computer-guided cutters that can fashion more complex shapes than a person working manually with hand-held tools. And computer graphics enable architects to explore sophisticated forms, while subjecting them to static analysis for safety’ [6].

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5 Work undertaken today of the Sagrada Familia began in 1979: http://mchurry.net/overview/
5.1 Stone Cutting

As far as we can see, the segmented arch and the tunnel vault also known as a barrel vault first appear as brick constructions in the 3rd millennium BC in regions where there was a shortage of wood, such as Mesopotamia and the valley of the Nile. Stereotomic stone cutting developed with the introduction of the voussoir. A voussoir is defined as a “wedge shaped stone with two oblique faces by means of which it rests on the adjacent voussoirs, laterally transferring the vertical forces due to its own weight and any other loads.” [8] Figure 1 illustrates a segmented arch composed of four voussoirs either side of a central key stone.

Figure 1: Segmented Arch with defined terms: [9]

The problem faced by medieval builders in the realization of vaults was how to cut the voussoirs constituting a structure. Aita implies that the medieval builders answered the structural questions, coincidently by solving the geometrical problems: symmetry, stability, material resistance and equilibrium of forces. Jacques Heymen, in „The Stone Skeleton” describing the design requirements for masonry arches, “failure of a masonry structure will occur when the line of thrust can no longer be contained within the stonework.” [10] He then describes in terms of design principles certain assumptions which can be made about the material. These include:

1. Stone has no tensile strength (assuming that the arch voussoirs are laid dry or with very little mortar).
2. The compressive strength of stone is effectively infinite.
3. Sliding of one stone upon another cannot occur. It implies that wherever there is a weak plane, for example between voussoirs, the line of thrust should not depart too far from normality to that plane.
5.2 Digital Stereotomy

The development of custom hardware for digital stereotomy is being explored by the Block research group in an experimental setup for automated fabrication of voussoir geometry for freeform masonry-like vaults. Through a combination of form finding techniques such as Thrust Network Analysis (TNA) and a four-axes computer numerical controlled (CNC) hot wire cutting technology, stereotomic methods driven directly by digital technology are being investigated. Specifically the geometrical interdependencies between the generation of the voussoirs and the physical limitations of the fabrication on the basis of structural information. “The principle is tested physically by cutting individual foam blocks, simulating the rapid and efficient cutting of natural stone with a diamond wire saw.” [11]

McGee et al. (2012) discusses several architectural processes, conceptual motivations, tools and techniques for the production of architectural volume. Using an inexpensive material Expanded Polystyrene (EPS) foam, which can be cut with a hotwire, “provides a method whose historical precedent can be associated with stereotomy and the developed surface of traditional stone masonry.” [1] Robotic hotwire cutting (RHWC) was explored as an efficient method as opposed to dedicated CNC machining. This has many advantages over traditional CNC milling at an architectural scale including reduced machining time, and a better surface finish. Whilst limitations may include higher production times, the limiting of available geometries to ruled surfaces and inaccuracies caused when dealing with the material variability.

The RDM Vault as shown in Figure 3, a collaborative project between Hyperbody and ROK- Rippmann Oesterle Knausse/ ETH Zurich, makes use of RHWC and explores a joint approach to the design and fabrication of vaulting
structures. This is where the components are nested completely within a volumetric block of material. Although this technique is limited to ruled geometries, the entire exterior of the component is shaped, and thus the aggregation can more accurately approximate a freeform surface. In this case the use of a robotic arm “typically costs less than half the price of a typically capable dedicated CNC machine.” [1]

![Figure 3: RDM Vault][1] Comparing the above approaches of Burry, Block and McGee et al raises the question of whether the same result can be set up with an industrial robot arm. In the case of Block “A customised machine setup was developed in respect to the technological, economical, and ecological relevant fabrication constraints.” [11] Burry states in regards to the stereotomic opportunities for the stone masons to sculpt and cut straight lines on corresponding 2D templates or “to automate this cutting process using contemporary robot stone cutting equipment.” [12]

McGee et al used a 6-axes robot arm and states that, ‘Dedicated CNC approaches are likely to always possess an advantage in terms of accuracy and overall capacity, but there are potential applications where the flexibility and portability offered by industrial robotic manipulators can fill a unique role in fabrication. Several researchers have tested applications for robotic wire sawing, but the capabilities of a robotically guided wire cutting operation to yield complex units in a finishes/semi finished state has not been studied extensively.’ [1]

In addition to the advantages outlined by McGee et al, the use of robot arms for fabrication has lowered the barrier to entry for architectural researchers and practitioners alike, as demonstrated by the establishment of the Robots in Architecture Association and international conference in 2012. The standard hardware platform, combined with integration layers for common CAD software, creates new opportunities for architects to experiment with novel stereotomic approaches.
6 Conclusion

The revival of stereotomy in the architectural discipline is due to four main factors. The aesthetic value; hidden externalities in production and transport influenced by sustainability; advancement of representational tools and developments in cutting technologies based on the industrial robot arm.

The change in the aesthetic value of stone is difficult to trace across the centuries. However it has always been a part of architectural construction, and we can speculate that it is inevitable that it will continue to be so in the future.

If we anticipate the actual cost of the production of goods will be reflected in their market pricing, that unpriced externalities will become priced, the very low embodied energy of stone will lead to its relative price decrease compared to other building materials.

The recent rapid rise of 3D modelling software and sophisticated digitally controlled tooling and cutting technologies adopted from the automation industry, allows for more complex structural investigation and form finding techniques. The instructional properties of software combined with a robotic arm can perhaps be compared to the methods in creating custom hardware in the development of stereotomic techniques cutting techniques.

The developments in computational tools have enabled the study of stereotomy to be more readily accessible to those who do not necessarily have the knowledge of advanced geometry. This consequently makes stereotomic information more widely appreciated and potentially used in the construction industry to create more varied, cost effective and sustainable solutions.

References

Alternative fabrication process for free-form FRP architectural elements relying on fabric materiality
Towards freedom from molds and surface articulation

Arielle Blonder and Yasha Jacob Grobman
Technion Israel Institute of Technology, Haifa, Israel
{arielleb, yashaj}@technion.ac.il

Abstract. FRP (fiber reinforced polymers) is a family of composite materials combining fibers and polymers to offer exceptional mechanical properties. Its unique material properties have led to its wide application across industries. Although we witness a growing interest in the material in the architectural field in recent years, a significant barrier to its application lies in the need for a mold. The paper describes a new alternative fabrication process for architectural FRP elements that relies on fabric materiality. It suggests a mold free process, combining form finding and garment making techniques, to allow for complex morphologies, surface articulation and variation. The paper describes both the fabrication process through physical experiments, as well as the design process through the use of two design software tools. It demonstrates the potential for sustainable variation of large component facade system.

Keywords: FRP, Fabrication, Architecture, Mold, Materiality, Variation

1 Introduction

A composite polymer is an engineered combination of fibers with a polymer matrix that makes it an extremely lightweight and strong material. The fiber reinforced polymers (FRP) family of materials combines fibers, such as glass fibers, carbon, and Kevlar, with polymers, such as epoxy, polyester, vinyl ester and nylon. As part of the ever-increasing quest for high-performance materials, the use of composite polymers has spread extensively in the past decades in numerous industries [1]. The main reason for its assimilation in industries such as the aviation, naval and automotive industries has to do with its high ratio of strength to weight and great durability [2-3].

Fabrication processes of FRP elements vary according to the type of industry and the characteristics of the final element. All conventional fabrication processes for FRP are based on molding. Among the most widely used molding techniques are contact molding, compression molding, vacuum molding, resin injection molding, and even injection molding with prepregs or filament winding, each of which require the use of a certain type of mold [2]. The cost of fabricating an element is directly connected to the chosen molding technique, the scale and the formal complexity of the element/mold. Since architectural elements are usually rather large, this technical aspect of the fabrication process has significant implications.
The paper proposes an alternative fabrication process for architectural FRP elements, that relies on the fabric's materiality. The new process eliminates the need for molds and facilitates affordable geometrical variation. The paper presents an experimental fabrication process that is an integration of a full-scale form finding process together with textile manipulations that are borrowed from the world of garment making. The paper describes both the design and the fabrication methods, via examples of digital design experiments and physical experiments. Together, it demonstrates the potential architectural applications, both as whole structures of small-medium scale and as large cladding component systems.

2 FRP and Architecture

Polymer composites, in the form of FRP, were first introduced to the architectural field in the late 1960s. Seminal experimental projects, such as Matti Suuronen's Futuro House or Buckminster Fuller’s Fly’s Eye Dome, were the first to apply the family of composite polymers to medium-scale structures. After two decades of relative abandonment, the material reemerged in the late '90s, influenced by the introduction of computation in architecture [4]. In the past five to ten years, FRP increasingly appears in architectural applications, both in experimental contexts and in commercial and industrial projects. It has been used only in particular situations, in cases where a high ratio of strength to weight and material durability were of major importance, or for repetitive elements where a single mold could be used to manufacture a large number of elements, or for large undertakings where formal complexity and surface finish were essential for the design.

Two generic modes of applications can be delineated for employing FRP in the fabrication of architectural elements. The first mode divides the basic element into a small number of large segments (e.g. the Chanel Pavilion, by Zaha Hadid1), while the second mode divides the large element into a large number of small components - either identical and repetitive, or diversified – which together form one system (e.g. the facade of the SMFOMA expansion, to be completed in 20162).

Along with FRP’s unique properties and the array of opportunities it brings, its application in the field of architecture faces some challenges. Both modes of architectural applications present substantial barriers due to the high cost of molds for each final element and the complexity of the assembly process. Contemporary architectural practices, such as the realization of complex freeform morphologies and the quest to improve performance through variation and differentiation, clearly highlight the limitation posed by the necessity to use molds, since such practices require numerous complex molds for each individual project.

Due to the size of large-scale architectural structures, the fabrication and manipulation of their molds turns out to be complex and highly expensive. While technically feasible, with the use of contemporary CNC technologies, the fabrication
of molds for architectural elements which are unique and non-repetitive, non recyclable and hardly reusable, makes the use of FRP inefficient and costly [5-6].

3 Searching for Alternative Molding Systems

The investigation of molding techniques and formwork systems has greatly increased in the context of this decade’s growing research interest in the challenge of realizing complex non-repetitive architectural forms. Two main directions are noted in this respect: making the molding system more efficient through reconfigurable molds (also referred to as moving molds), which enable the multiple usage of molding, and creating moldless form-making techniques that rely on form-active structures. Reconfigurable molds (e.g. ADAPA Adaptive Molds from Denmark, North Sails 3DL molding technique from the United States and FlexiMold from the Netherlands) rely on a complex mechanical system of moving pistons, connected directly to the CAD software; these are mainly used as an offsite casting process, whether for polymer composites or concrete materials [6]. Moldless form making techniques rely mainly on form-active surfaces, and are the product of the contemporary elaboration of simple systems, based on advanced modeling and simulation tools. Form-active structures redirect external forces primarily through the form of their material. Flexible fabric formwork systems make use of form-active structures as the molds for surface-active elements, such as shells. They relate to the long-time tradition of form-finding: a design/fabrication process in which form is not defined by the designer but rather generated by the definition of boundary conditions, and the self organization of the material under those As such, flexible fabric formwork optimise naturally in response to given conditions since the material presents no resistance to compression and configures itself into optimal form when under tension. [7]. Fabric based molding systems exist in all types of form-active structures: under compression (such as air-formed concrete) or tension (such as fabric formwork).

Air Formed Structures, or Pneumatic Formwork, are membranes which are pressurised to temporarily support the reinforcement and the concrete mix until it is cured. The concrete may be placed outside or the inside the membrane. This type of fabrication process produces only synclastic morphologies, which is one of its greatest limitations. Pneumatic formwork is still used, with a renewed interest in the "Bini-shell system". On that basis, other inflatable formwork systems are currently being developed, like the "wedge system", in TU Vienna [8] and the "Concrete cloth shelters".

Membrane Casting (of Fabric Formwork) is the casting of wet concrete into a thin formwork membrane that deflects into a repertoire of precise tension geometries forming convex surfaces under the viscous pressure of the cast material. This produces naturally efficient structural curves of unprecedented sculptural forms of

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3 The Bini-Shell system was originally invented in the 1960's by Dr. Dante Bini, who built 1,600 of them in 23 countries. http://www.binishells.com/systems/systems.html
4 http://www.concretecanvas.com/
extremely light formwork and extraordinary surface finishes. Fabric formwork has been extensively researched, for the structural optimisation it offers, for the sustainable approach, minimising efforts invested in molds, and for the texture finish it gives to the elements. Current advances in simulation and the integration of digital tools drive potential applications further. Their combination with other forming systems within the process, expands the present somewhat limited repertoire of geometries and opens up future prospects.

Tensile membranes are being used for different alternative molding systems, most of which aimed at the creation of double curved concrete elements. The approximation of a target surface to be built, by the geometries afforded by the molding system is challenging. The use of stretched fabric over flat rigid curvilinear frames as a mold for FRP elements is demonstrated in the canopy-like structures of "Pleated shell".

Although complex and varied in its outcomes, it should be noted that the main limitation of these systems is that the final shape derives from the material’s adaptation to forces; thus, it is restricted to a specific family of morphologies. Pronk tackles the limited morphologies implied by such form-active molding by combination of different systems (pneumatics, cable nets and tensile membranes). Potential further expansion of the repertoire of shapes and structures is suggested by the combination of a FRP mold and a concrete cast elements, forming an anticlastic saddle surface.

4 Fabric Materiality in FRP Fabrication Process

FRP is composed of fiber material, mostly in the form of woven textile. In its various standard fabrication processes it makes use of the capacity of textile to adapt to the given form of the mold, under pressure. The basic fabrication process consists of the layering of several fabrics over a mold, their impregnation with resin, and the curing of the whole under heat. The layering of material is designed based on the calculation of the various parameters concerning the fabric (such as weaving type, weight), to enable a perfect drape over the mold, for maximal adherence to the shape with minimum wrinkles or encapsulated air. The resulting element does not reveal the fabric materiality of its textile component in its morphology, nor rely on it in its fabrication process.

Several experimental projects in recent years have tackled the issue of FRP form-making, on the fiber level, developing direct fiber placing techniques (such as filament winding). The use of robotic arms for the direct placement of fibers (of glass and carbon) over simple two dimensional molds for the fabrication of complex double...
curved elements is demonstrated in two research pavilions by the ICD (Institution for Computational Design in the faculty of architecture and town planning in Stuttgart), by Achim Menges, in close collaboration with Jan Knippers from the ITKE (the research pavilions of 2013-2014\(^7\) and of 2012-2013\(^8\)) [14]

A similar aim for alternative fabrication of complex three dimensional components, by manual means of direct placing of fibers is demonstrated in the "C-Lith" installation.  

Aiming to achieve formal complexity and discard the core mold, as described above, the experimental fabrication process described in this paper also suggests an alternative form active fabrication processes for FRP, relying on fabric materiality. It focuses on the fabric characteristics of the fiber elements in composite FRP and its self-organizational properties. Using ideas from the body of research on form finding in architecture, and learning from fabric formwork methodologies, this study investigates ways to develop a design and fabrication method for the generation and fabrication of complex geometry architectural elements using FRP. Adapting textile attributes and manipulation techniques from the world of garment making, the suggested process seeks for the introduction of surface articulation and complex forms into the fabrication of FRP elements. It suggests the freedom from molds, by treating the FRP as hanging membrane, and proposes ways for local differentiation of the surface for performance, optimization and ornamentation.

Fabrics can bend in multiple directions, creating three dimensional forms with double curvature with large deformation under low stresses. A structural stability and a spatial organization of a greater order can be gained with low energy actions. Man has channeled the pliability of fabric and its self organization for the achievement of a desired structure since early days of human history for clothing fabrication, by manipulating fabrics in various ways. Simple manipulations such as stitching, gathering, pleating, furrowing and many more transformed flat fabrics into complex three dimensional structures in space.

The variety of manners by which form is obtained in textile is demonstrated in the garment-making discipline and can be placed under four main categories: the drape, being a fabric's property, pattern-making and fabric manipulations, being tailoring practices and "fully-fashioned", which is a fabric material construction.

Out of these four categories which constitute the fabric materiality, the experimental fabrication process described in this paper is making use of the drape and some fabric manipulation techniques, Pattern-making and fabric construction ("fully fashioned") are not in the scope of this experiment.

\(^7\) http://icd.uni-stuttgart.de/?p=11187
\(^8\) http://icd.uni-stuttgart.de/?p=8807
5 Alternative Fabrication Process in FRP

Developed from an earlier technique devised by Blonder [16], the method essentially involves hanging up a textile membrane (such as woven glass fiber or carbon fiber) impregnated with resin, then curing it and overturning the result, to obtain a shell-like structure (Fig.1). The shape obtained is defined by the drape, which can be manipulated by variations in the amount of material, insertion of lines of stiffness (such as the seam) and changes in its orientation. Fabric orientation is defined by the Grain - the orientation of the yarn within the fabric, running in three possible directions: lengthwise (the warp direction of the weave, has less stretch), crosswise (the weft direction of the weave, more stretchy then the lengthwise) and the bias, at 45° to both lengthwise and crosswise. (45° being "true bias", while all other angles between the two perpendicular grains defined as "simple bias"). The bias is the grain allowing the most stretch in fabrics; when a fabric is cut in the bias, shear resistance decreases, so that the flat surface deforms in-plane.

![Fig. 1. Basic fabrication process Upper Left: (a) hanging. Lower Left: (b) curing. Right:(c) inverting. Prepreg Carbon 0/90 Twill, 600 gr/m²](image)

On top of the described basic process, features and manipulations are introduced. The further elaboration of the basic assembly processes in garments is considered as fabric manipulation. These manipulations introduce local three dimensionality in the two dimensional fabric, altering its surface and organization in space. The extremely rich array of different traditions, techniques, methods and tools, can be classified through the process of their making: by needle, by pressure and by heat. Although described as separate practices, often times these are combined in craftsmanship, for the elaboration of a surface, or a garment. The features introduced in this experiment are borrowed both from the world of sail-making, like the corner reinforcement
feature (Fig.2), as well as from the world of garment making, like the cuts and pleats (Fig.3). They potentially serve a range of performance purposes, such as structural or acoustical behavior, as well as serving for the articulation of the surface, for differentiation and functional ornamentation.

**Fig. 2** (left) - Corner reinforcement by local additional layers of directional fibers. Pre-preg Carbon 0/90 Satin, 200 gr/m². (right) schematic layering pattern.

**Fig. 3** - cuts and pleats for surface articulation. Pre-preg Carbon 0/90 Twill, 600 gr/m²

The proposed fabrication process consists of the following detailed stages:

- *Tailoring composite woven fabrics to the desired shape*: Fabrics can be of varying fibers, thickness or weaving pattern. Prototypes of the process were realized both in carbon fiber and in glass fiber fabrics, using both wet lay-up and dry lay-up processes (pre-pregs).
- *Layering fabric plies*: Layering can differ throughout the completed piece in the number of plies, the types of fabrics and the cut shapes
- *Placing features*: Various techniques and manipulations from the world of garment-making – such as cuts, stitches, pleats, pinches and ruffles – can be applied to locally manipulate the morphology.
Setting the anchoring points and hanging the membrane: Fabric is hung from different anchoring points, at the specified heights. The phase of impregnating the fabric with resin will depend on the chosen resin system: wet lay-up systems (hand impregnation or spraying) will be applied just before hanging the membrane, while dry lay-up (pre-pregs) do not require an impregnation phase.

Curing: The curing process is selected according to the chosen fabric and resin system.

Inverting the stiff cured structure: Once the element is cured, it is stiff and can be inverted. Depending on the element’s scale, this phase might require machinery (cranes, lifts, etc.). Post-curing treatment of the inverted structure can include surface finishing such as sanding, coating and painting. The inverted structure will require further treatment for its placement and subsequent anchoring to the ground.

A large prototype structure was realized, measuring 200(W) 1000 (L) 100(H) cm. (Fig. 4). It incorporated the following features: large opening, cuts, stitches, slots, pinch, pleats and corner reinforcements.

Fig.4: Large prototype incorporating various features. Pre-preg Carbon 0/90 Satin, 200 gr/m². 3 plies+corner reinforcement

6 Simulation Based Design Process

As the fabrication process is a full-scale form finding process, the form of the resulting element is the outcome of the self-organization of the material according to its properties, the boundary conditions and manipulations applied on it. Therefore, it cannot be designed directly as a simple 3D object, but requires a simulation engine for its design, that will emulate its fabrication process. Such simulation can be realized through several digital tools, of different type. While the full physical simulation of draped fabric is still a complex computational challenge [17-18], computer based form finding (real-time physics simulation) is gradually becoming more easily
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accessible, aided by tools such as Kangaroo Physics (add-on for Grasshopper parametric platform in Rhinoceros 3D modeling software). On a different angle, 3D modeling, animation, and rendering software, such as 3DSStudio MAX, offer high definition cloth simulation tools. In the framework of such simulation tools, it is possible to calculate the behavior of a fabric under gravitational load and other external physical forces, and introduce changes in the boundary conditions (e.g., the position of anchors and height) that are directly reflected in the fabric’s drape simulation. The required final form is the result of an iterative process in which the obtained shape is visualized through dynamic digital simulation.

During the current stage of the research, digital experiments were conducted through two types of simulation engines: real time physics by Kangaroo for Grasshopper Rhino, and cloth modifier in 3DStudio Max. As each of the engines targets different types of markets, they differ in many aspects such as their logic of modeling, manipulation capabilities, detailing, accuracy, end result and ease of interface with other digital tools. As a parametric software tool that is oriented towards the architectural field, Kangaroo physics easily simulates the form finding process of hanging membranes in the digital realm under physical laws. Its model is based on damped springs connecting abstract particles, over which various physical forces are applied. The character and behavior of the fabric are defined through its springs characteristics, connecting the abstracted particle mesh of the fabric. Boundary conditions, such as anchor points, and external physical forces, such as gravity or wind, are easily defined and can be the dynamic result of different parameters internal or external to the grasshopper tool itself.

The Cloth Modifier in 3DS Max is oriented towards realistic animation, and incorporates within it a modifier, which is based on a garment making logic (panels, seams, tear lines etc.). The character and behavior of the fabric can either be selected out of set of presets of fabric types, or can be defined through a table of parameters (such as bend, stretch, plasticity, density etc.), which consider the anisotropic character of woven fabric (by U/V definitions). Features such as holes, seams, tears and folds can be easily defined, through the "Garment maker" modifier, and other manipulations of the fabric can be defined by coupling to other dynamically animated objects in the scene. (See Fig. 5)

While Kangaroo Physics facilitates the optimization process of the global shape by draping and the variation of constraints in a parametric method, the Cloth modifier can embed fabric manipulation features in the simulation, for the surface articulation and differentiation. For both tools, the simulation process necessitates a process of calibration between the digital virtual realm and the fabric’s physical materiality. It is material specific and requires the translation of physical material properties as parameters in the simplified digital simulation interface
Fig. 5: Upper left: Stitch feature in physical model. Upper right: Stitch feature in digital model. Lower left: Pinch feature in physical model. Lower right: Pinch feature in digital model. All digital models were realized by Cloth modifier in 3DSMax. Top physical model is realized in carbon fiber prepregs, bottom model is realized in wet lay-up fiberglass.

7 Potential Architectural Applications

The introduction of full-scale form finding as the fabrication process of FRP for architectural elements is mainly envisioned for two project types: The first type is small to medium structures of complex free form morphology, treated as one whole form. The second type is large cladding systems based on varied small-sized components of complex double curved geometry. Entire structures, in small to medium scale, can be rapidly erected in a process where structural optimization is naturally embedded in the fabrication process. It can enable the erection of structures where FRP serves both as structure and as skin. The formal language of such a structure would naturally derive from hanging membranes and their manipulation. The fabrication of such a structure would typically take place on site.

Cladding systems, can tolerate local variations, as they are comprised of components that can be differentiated. The difference in form does not imply the fabrication of a new mold, but only simple changes in boundary conditions and fabric manipulations, which are easily obtained. The fabrication of such components would typically take place off-site, and would be easily transported to site, like conventional facade elements.

Fig. 6: A suggestion for a small-medium type structure, a pavilion based on two rings, hanging cloth tailored with slots (a) Digital model in initial state, tilted upper ring (b) Digital model in draped state, with a twist of the lower ring, after Grasshopper simulation (c) final mesh, flipped structure (d) Rendering
8 Case Study - A Differentiated Facade

The application of the suggested fabrication process for a component system is demonstrated through a digital experiment. A Kangaroo definition for Rhino Grasshopper was written, simulating the draping of different rectangular surfaces. The whole design is parametric, and could afford a large number of components. (Fig.6) To avoid long calculation times and for efficiency reasons the detailed demonstration is realized over an array of 6X4 panels.

Fig. 7: A low-resolution simulation of a large amount of components, an array of 25X10 panels

All panels are of identical size, and have the following constraints applied on them:

- All panels are subdivided in identical resolution (10X10)
- All panels have same “fabric characteristics” (stiffness value of mesh springs)
- All panels are constrained in four corners (with an internal offset from the panel's size in rest length, for its drape)
- All panels are subjected to gravity

The fabrication process simulated in the grasshopper definition consists of the placing of four anchor points at the corner of the fabric panel, and the hanging of the membrane at a set distance between them (the offset). A simple “pinch” manipulation is applied over the fabric. In the definition, an anchor spring of one vertex is added within the panel's area. This additional anchor creates the Pinch feature demonstrated above (see Fig.5), in both physical and digital models. The parametric platform of grasshopper easily generates a different anchoring point for each panel. For the demonstration, two models were realized, differing only in the logic of generating the different anchoring points (see Fig.8).
It is important to note that the fabrication of such a set of panels does not require a different mold for each panel, as it would be done in conventional FRP fabrication processes, but simply a different hanging point of the Pinch. Nevertheless, morphological difference between the panels is clearly noticeable. As the anchoring points at the perimeter of each of the panels are identical, the different surfaces can all be easily connected to a standardized building system, such as the building’s facade, as demonstrated by the schematic cylinders in model A (See fig.9), connecting the panels and the back surface.

**Fig.9**: Left: model A with anchoring points distributed by an incremental series. Right: Model B, with anchoring points distributed according to attractor curves.

### 9 Conclusion and Further Research

The paper describes an alternative fabrication process of FRP architectural elements, based on the notion of fabric materiality. It suggests a mold free fabrication process that draws from the world of architectural form finding and garment making, to allow complex morphologies. The integration of fabric manipulation features articulates the
surface and generates variation while suggesting sustainable large differentiated systems.

The suggested approach supports architectural applications for small-medium structures and large-scale component based cladding system. Previous stages of this research had demonstrated the feasibility of fabricating small-medium structure. This paper concentrated on the examination of the potential for the implementation of the suggested approach as a cladding system for a large-scale structure.

For both structure types, the surface of the elements could be articulated by fabric manipulations (stitches, folds, cuts, etc.) to obtain specific performance requirements such as ventilation, reduction of weight, flow of forces, acoustics, stability and insulation. These mechanisms should be further elaborated to form a tight link between the resulting performance and the surface articulation techniques. The design method has been tested while employing two different design software tools, each presenting different advantages and drawbacks. Further research is needed in this realm in order to be able to determine conclusive recommendations regarding the optimal tool for this process. Future research should involve the examination of tools from related disciplines such as fashion design (e.g. Optitex\(^\text{10}\)) or dedicated FRP laminate modelers (e.g.Patran\(^\text{11}\)). A simple flow of design and fabrication of differentiated FRP elements for architecture can be suggested, requiring additional physical experimentation and digital modeling research.

The freedom to generate variations and the release from the constraints of needing a mold, as suggested by the design and fabrication method described in this paper, has the potential to drive future architectural applications in FRP toward differentiation and responsible complexity of form.

\(^{10}\) http://www.optitex.com/Pattern-Making-Suite [20-1-2015]

References

Transient materialization

Ephemeral, material-oriented digital fabrication

Shih-Yuan Wang¹, Yu-Ting Sheng², Alex Barchiesi¹ and Jeffrey Huang¹

¹École polytechnique fédérale de Lausanne
²Swiss Federal Institute of Technology in Zurich
shih-yuan.wang@epfl.ch

Abstract. This paper introduces the notion of transient materialization through an exploration of the relationship between digital and material-based digital fabrication. The research was inspired by direct observations of nature’s beauty in the form of thin films. The building block of the experiment is an n-hedron structure composed mainly of soap foam, which is blown into a foam structure. The paper questions this structure’s materiality, examines its physical performance and ephemeral characteristics, and expands on its meaning through an experiment in digital fabrication. Specifically, this experiment demonstrates various configurations of dynamic and programmable foam structures on a large scale of fabrication. The fabrication interacts with the algorithm, which involves a mixture of air and helium (controlled by pneumatic valves), as well as additive chemical substances and thickening agents, all of which exist in a certain space and time.

Keywords: digital fabrication; ephemeral; foam structure; dynamic and transformable; algorithm; chemical substances

1 Introduction

The development of computer-aided designs (CADs) from two-dimensional systems to three-dimensional modelling has enabled architects to digitally simulate and visualise different geometric models in a Cartesian coordinate system. Moreover, with the recent emergence of parametric design modelling, the methodology of generating architectural forms has shifted from the traditional geometric modelling system to associative design modelling [1]. Through the use of this digital and adaptive system, the development of digital fabrication technologies in architecture has been greatly enriched and improved. Data, materials, and construction can be interwoven within this system, which allows architects to control and adjust the process of fabrication.

Digital fabrication technologies, such as CNC milling, 3D printing and robotic fabrication, are rapidly becoming common practice in architecture, and such technologies are currently being explored experimentally to develop prototypes and pavilions. This discussion does not seek to emphasize how these techniques can be applied to the large scale of buildings; rather, its concern is to challenge and
investigate an innovative and novel technology in order to influence design and architectural thinking [2].

This research pursues the notion of transient materialisation to investigate the new design approach of digital fabrication. Transient materialisation proposes immaterial architecture [3] as the impetus for investigating new possibilities and cognition of morphology in architecture through space and time. In addition, the definition of immaterial architecture does not dichotomize architecture as either material or immaterial; rather, it emphasises the invention of an ephemeral dynamic, generated as a result of the capacity of a machine or the properties of materials, information or external environments. Thus, to address the challenge of this novel design in digital fabrication, this process involves experimenting with the physical and chemical properties of materials in combination with digital tools and machines. The potential of the material, combined with environmental conditions, determines the existential path of the shape, from transformation to disappearance. In other words, this paper claims that architecture may no longer focus on durability (i.e., the quality of a building) as defined by Vitruvius in De architecture [4]. Instead, it not only accepts and embraces the concept of ephemerality to represent the tension among perception, contingency, improvisation and immediacy, but also does so within a transient moment that offers a new possibility in architecture and digital fabrication.

This experiment was inspired by the spherical membrane of the soap bubble: a thin film of soapy water that usually has a lifespan of only a few seconds. In losing its spherical geometry, a soap bubble forms a foam based on n-hedron structures joined together. Through an understanding of the properties of soap foam bubbles, the first phase of machine was produced to generate a moving, transient, and ever-changing three-dimensional foam structure controlled by a mixture of detergent, chemical additives, thickening agents, and gas, facilitate by the mechanism and digital information. The dynamic foam structure follows two principles: 1) the shape output is computationally controllable through pneumatics, mechanism, and a pre-defined structure; 2) the real-time transformation and disappearance of its form is determined by the intrinsic properties of the material, the additional substances, and the environment.

This paper first describes the existing works that inspired this experiment. Second, it explains the focal system, including a technical and mechanical overview, the consideration of additive chemical substances and thickening agents, the dynamic and physical experimentation with the foam structure, and the current results of test. The following are the contributions of this project:

- a description of transient materialization, which may trigger the pursuit of new possibilities in digital fabrication;
- the creation of first prototyping machine for programmable foam structures; and
- the development of a framework for developing and testing the materials, mechanisms, foam fabrication processes, and control systems needed to generate a foam structures.
2 Context and Previous Experiments

Several previous works have focused on the notion of transient materialisation. The *Pepsi Pavilion* built by Billy Klüver and E.A.T. in the 1960s; Diller and Scofidio’s *Blur Building* of 2002; *Cloudscapes* by Tetsuo Kondo Architects and Transsolar in 2010; and *Waterfall Swing* by Dash 7, in collaboration with Mike O’Toole, Andrew Ratcliff, Ian Charnas and Andrew Witte, in 2011, all show the influence of immaterial architecture. The *Pepsi Pavilion* (Fig. 1) was perhaps the first collaboration among artists, architects, engineers, and scientists to produce an experience of virtual illusion. The outside of the dome was covered in a water vapor cloud sculpture by Fujiko Nakaya. The system monitors humidity and wind, using nozzles to produce a volume of cloud with a low-hanging effect [5]. The *Blur Building* (Fig. 1) is another instance of a dematerialized architectural achievement combining architecture and technology. In this project, mist nozzles were used to construct a pavilion whose appearance could be changed by the weather. For example, the mist tends to spread out to the surrounding environment if the weather is hot and humid. When the day is less humid, low-hanging smoke appears and follows the direction of the wind. On a cool day, the fog ascends into the sky and evaporates. [6] *Cloudscapes* (Fig. 2) also used fog to create an artificial cloud at a certain height in space, offering different atmospheres through which visitors can travel in the space of a spiral stairway. Finally, *Waterfall Swing* (Fig. 2) developed differently patterned walls of water, which were computer-generated and operated by multiple independently controlled solenoid valves at the top of structure.

Fig. 1. Left: The Pepsi Pavilion [7]. Right: Blur Building [8].

Fig. 2. Left: Cloudscapes [9]. Right: Waterfall Swing [10].

Many of the projects described above envisage new possibilities for an architecture utilizing cross-disciplinary collaboration to develop more responsive spaces for living. Inspired by these projects and perspectives, this paper explores transient
materialization to propose that the complexity and perception of architecture may be grounded in the idea of immaterial architecture—an idea that can be explored through the integration of various material potentialities and through examinations of their physical behaviours, of machines, of digital information and of space. In addition, the aim of the project is to take architecture beyond the creation of static forms and into the design of dynamic, transformable and ephemeral material experimental processes.

3 The System

3.1 The Design Process and Technical Choice

The system consists of two main components: a foam-generating machine and a mass supply (Fig. 3). The foam-generating machine comprises a container for filling with liquid, two input openings in the bottom for solenoid valves, a fabric to determine the initial phase of bubble size, a sculpture mechanism, and a shell to support the container and sculpture device. The mass supply includes a helium bottle, an air compressor, a liquid distributor (i.e., a detergent with chemical substances and thickening agents and a pump machine), and control circuits. In this experiment, the control system is composed of an Arduino, solenoid valves, stepper motor driver boards (Big Easy Driver), stepper motors, DC motors, and a water pump. Solenoid valves are used mainly for the adjustment of air and helium, while the sculpture machine with two stepper motors, two DC motors, and two sharpeners are used to adjust the appearance of the foam.

Fig. 3. (1) Foam-generating machine, (2) Mass supply.

Through the integration of two components, the following are generated through the process of the foam structure within this system: In the initial phase, the foam-generating machine is filled with detergent from an external liquid container. The
additional chemical and food substances, which are thicker, as well as the humectant, are added to strengthen the bubbles and decrease the evaporation of soapy water. After the first step, a growing and successive foam structure is produced through the mixture of air and helium, which can be regulated and adjusted by pneumatic control valves. The two solenoid valves are installed in the bottom of machine. The diameter of passage for the pneumatic valves are 1.6 mm, and the maximum work pressures are 4 bars. The values for the parameters of air and helium solenoid valves are determined by predefined shapes. However, due to the sensitivity of the soap bubbles to different environmental conditions, these valves are adapted to reach the same results. Furthermore, the appearance of the foam can also be slightly altered through the sculpture mechanism, which consists of two sharpeners, while the foam grows upward.

3.2 The Substrate: Chemistry Considerations

The foam structure is composed of soap bubbles, which can be rapidly dehydrated and disappear into dry air. Thus, for the sake of preventing the explosion of the bubbles during the generation process and in order to prolong the life span of bubbles, this project experimented with a mixture of chemical substances and thickening agents, including as glycerol (C\textsubscript{3}H\textsubscript{8}O\textsubscript{3}), corn starch, and detergents (Fig. 4). Glycerol (also called glycerin) usually is used for skin moisturizing lotions and is highly hydroscopic, which means that it has the ability to attract and hold onto water molecules to prevent the evaporation of water. In addition, corn starch as a ingredient in liquid-based foods, such as soup, and it is able to create a thick and viscous soap that allows for blowing long-lasting bubbles [11].

![Fig. 4. The explosion of bubbles during the generation process.](image)

3.3 The Mechanical Devices

For the purpose of maintaining the contour of the foam structure and preventing redundant bubbles from accumulating on the top of machine, this project developed a mechanism that sculptured the appearance of foam during the process of growth. This device is installed on the top of the machine and consists of stepper motors, DC
Transient materialization - Ephemeral, material-oriented digital fabrication

Motors, sharpeners, and a supporting structure (Fig. 5). The stepper motors are used to control the degree of a set of gears, which determine the width of the foam structure. The sharpeners are driven by the DC motors to engrave the foam. According to the properties of soap bubbles, a higher degree of stepper motors may affect the stability of the foam structure and cause a splitting effect while the foam grows upward.

![Fig. 5](image-url)

**Fig. 5.** (1) Stepper Motors, (2) DC Motors, (3) Sharpeners.

### 3.4 Dynamics and Physics of Overall Experimentation

This experimental work developed various shapes of foam structures and presented a strategy for increasing the lifespan of foam and balancing its structure in a real-world environment. In addition, through a series of trial-and-error laboratory tests, this experiment found the adjustment of helium and air solenoid valves and an appropriate chemistry to be key points in determining the stability and the average life span of the foam structure. Specifically, two possible methods of generating foam structures—the direction of growth (i.e., a straight and an arc foam structure), controlled by the output of pneumatic valves, and the different pattern of foam structures, determined by sculptural mechanisms—were shown through pilot experiments that took these factors into account (Fig. 6).
Fig. 6. Left to right: Straight foam structure, arc foam structure, foam structure with a sculpture approach.

The straight foam structure is balanced mostly by the switch controlling the air or the helium solenoid valve during the iteration process (Fig. 7). In this control system, there are four parameters (i.e., the counters for generating helium and air in a specific time period and the output values of helium and air) that need to be adapted automatically throughout the iteration. The switch between the helium valve and the air valve is constrained by the parameter of the counters. Moreover, in order to build a higher structure, after reaching the maximum number of counters, the output values and time periods of helium and air are gradually decreased for each iteration. The chemical additive and thickening agent (i.e., glycerol and corn starch) are added to the detergent to prevent the explosion of the bubbles, which could interfere with the performance of the foam structure.

Fig. 7. The generating process of straight foam structure.
The method of generating the arc foam structure was developed through previous experiments with the straight structure and through a new method that allows for the manipulation of the direction of growth (Fig. 8). The difference between two modes results from an adjustment to the helium and air valves. Within the iteration, the first time period produces only air in the machine, and then switches to the next step, which delivers both helium and air at the same time. The reason the foam structure grows to the left is that the air valve is installed in the bottom left side of machine, with the helium valve on the opposite side. The bubble on the left side, which contain more air, are heavier than the bubbles on the right side. In order to complete the whole shape, the method of producing the straight foam structure is immediately followed by the first phase.

The final approach of sculpturing foam was generated based on the parameters of a straight foam structure and in combination with the movement of the mechanism located on the top of the machine. The appearance of the foam structure was shaped by this device, which consists of stepper motors that manipulate speed and create continuous angles as the foam grows upward (Fig. 9).
3.5 Result

This paper presents two strategies to achieve anti-gravity and programmable foam structures. In this project, the first priorities were the material components and ratio, which served to strengthen the bubbles. As shown in Table 1, glycerol and cornstarch were added to increase life span and prevent explosion of the bubbles. The results showed that the first method of producing foam structures (i.e., straight and arc) can allow them to exist for approximately twelve to fifteen minutes in space. The average life span of foam structures made with the sculpture process is less than ten minutes due to fewer bubbles. Finally, in this experiment, the maximum height of the structure was found to be approximately 1.5 meters (Fig. 10).

Table 1. Ingredients and the examination of explosion and duration of soap foam.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Water (liter)</th>
<th>Dish Detergent (ml)</th>
<th>Glycerol (ml)</th>
<th>Cornstarch (ml)</th>
<th>Explosion (yes/no)</th>
<th>Duration (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>500</td>
<td>15</td>
<td>500</td>
<td>no</td>
<td>12-15</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>500</td>
<td>15</td>
<td></td>
<td>yes</td>
<td>4-5</td>
</tr>
<tr>
<td>3</td>
<td>6</td>
<td>500</td>
<td></td>
<td></td>
<td>yes</td>
<td>3-4</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>60</td>
<td></td>
<td></td>
<td>yes</td>
<td>3-4</td>
</tr>
</tbody>
</table>

4 Conclusion and Further Step

The aim of this paper was to introduce transient materialisation as an approach for designing dynamic, transformable, ephemeral and material-based digital fabrication. The purpose of this novel design approach is to argue that an architectural work is not simply a retinal image [12]; instead, architecture coordinates materials that are both embodied and spiritual in essence, ultimately creating a perceptive experience of space. In this project, the foam structure, as an architectural object, is generated by the machine. Due to the intrinsic nature of the material, the structure acts as an organism: moving, transforming, responding and disappearing according to its surroundings, the time and the user. In this way, the floating, uncertain and blurred object of the foam structure induces and enhances the perceptive experience of body in space and time. Through this interaction among object, user and space, architecture may exist between rationality and sensitivity, thus becoming open to an interpretative creation of the conception of space.

This paper contributes to and demonstrates how and why the system to generate foam structures works. However, the current machine is limited to certain strategies. Further research within this project will involve a re-consideration of additional chemical substances designed to increase the lifespan of the bubbles. In addition, different types of foam structures, such as three-dimensional curves, will also be further investigated. Finally, a temporary pavilion will be a further consideration for the application of this project.
Fig. 10. A large scale of arc foam structure.

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Digital fabrication in Brazil
Academic production in the last decade

Elza Luli Miyasaka\textsuperscript{1} and Márcio Minto Fabricio\textsuperscript{2}

\textsuperscript{1}University of São Paulo
\textsuperscript{2}Barão de Mauá University Center
{elzamiyasaka, marcio.m.fabricio}@gmail.com

Abstract. This work aims to review the literature on digital fabrication verifying the Brazilian status on a general view. Concerning the methodology, the research was carried out from 2004 to 2014 analyzing three aspects: 1. the situational context of digital fabrication; 2. digital fabrication in the design process; 3. the Brazilian status. The findings revealed the use of digital fabrication is mainly focused on the design process. Also, the most common objects in the research are the development of models, furniture and pavilions. Moreover, digital fabrication is increasingly being inserted in the syllabus of architecture schools. Brazil strikes in object production both in quantities and interests throughout the country.

Keywords: Digital Fabrication; design production, literature / review; CAD/CAM architecture.

1. Introduction

One of the main uses of Digital Fabrication refers to the fabrication of curtains and carpet in the beginning of the XIX century. The information was transmitted through little holes on a hard paper which signaled positive or negative commands to the loom machine which would insert different string colors creating various patterns previously set up. According to logical computer matrix, such a codification became electronic data and the principles remained the same along time. In the 70’s, Ronald Resch at the University of Utah built an eclipse through CAD system and cut metallic plaques by a computer, a design known as Ukranian Easteregg [1].

In current researches, one of the main examples of digital fabrication was the Disney Concert Hall in Los Angeles of the architect Frank Gehry. In the design, the titanium plaques with carved surfaces which sealed the building were shaped by an aerospace system and the computers controlled the milling machines toward its structuring [1].

In digital fabrication the machines that are controlled numerically can be programmed from the computers as it follows:

\[\text{[...] the key task in manufacturing and constructions is to convert geometric models (state descriptions of objects) into sequences of machine instructions (process descriptions) [1].}\]

The process was described according to the diagram as it follows:

![Diagram of fabrication process](image1)

A machine receives instructions toward element elaboration which can come directly from a numerical programming or data previously set up by the factory. Such data from a design can be a geometrical model or reversed engineering; the process demonstrates a flow of information which is either organized for production or brought through the production machinery.

The digital fabrication process has been through an improvement since the middle of the XX century in the development of spaceships and submarine capsules. Among differentiated possibilities there are the use of the programs CAD, CATIA\(^1\) and CAM\(^2\) in programming the studies for object building [2]. It is a process from design to construction in which it is necessary the translation of designing graphical representations into data, which will be translated to the production machinery. Some translation aspects are related to the connection between the architect and the machinery capacity. That raises the need of architects understand how those tools run, what types of material are applicable, also where the opportunities are toward new possibilities [3]. Find below a diagram for model production that uses machinery for fast prototyping [4].

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\(^1\) Computer Aided Three-Dimensional Interactive Application

\(^2\) Architecture Manufacturing Design
In the diagram above, there are subsequent steps; in the first one the concern is toward the main characteristics of the physical model such as scale, object, etc. The author mentions that in digital data models, different from traditional ones, it is possible to reach higher accuracy and sharpness having better details of the building.

In the second step, when techniques and materials are established, there is the importance of assertive and integrated choices within techniques, machines and geometry which will be applied in the model, as some types of geometry can only be produced under specific techniques. In the third step, it is the moment to produce the files to be addressed to the machines. Those data are generated in drawing, similar to the traditional models, instead in the digital format. In the fourth step, the pieces are produced generated by the machines, which in turn, receive digital data and will transform them in pieces assembled and finalized in the fifth step.

In both commented diagrams, the authors did not mention the increasing information with more complex surfaces; in those cases, the generated data are also more complex in addition to being generally associated with designs to specified piece production through algorithms.

In 1995, it was already discussed ways for the development and production of architecture. It was mentioned the needs for architectural codification, moreover the use of modelling and evolutionary forms in machinery applying it to design development [5].

A more significant requirement is that of materialization into a buildable medium. This could be achieved by making part of the code simply representing a material and a precise construction technique [...] final transformation should be process-driven, and that one should code not the form but rather the precise instructions for the formative process [5].
For the production of buildings with elements produced digitally, the challenge has been to interpret data appropriately by designers applying parametric relations. This transformation involves the surface elaboration of various parts as the machines would perform cuttings, forms and component drilling. For example, on performing a decreasing spiral cover carried out in 1990 by the CAD system, it was elaborated over 300 individual panels. Nowadays, it could be performed faster and probably under lower cost. The algorithm production would produce defined panels for the machine, according to the specification of the architectonic design as well as the edge details necessary to avoid water infiltration [6].

Production can be characterized by the target, number of working axes, also object production means which can be studied, that is, models and prototypes are named under fabrication or digital manufacturing [9].

Digital fabrication is a posterior phase to the concept process and a fabrication method under digital data; however the designer needs to verify and analyze the fabrication process longer before the object concept phase [7]. The production strategy can be: 1. 2D fabrication generally using CNC cutting, works with shaping, triangulating or polygon, reproducing deformable surfaces or unfolding. They are related to the creation of flat components for structures and surfaces. 2. Subtractions are related to the material removal from a solid surface, the CNC Milling is a kind of computer-driven equipment with a cutter for sculpting. 3. The addictive system, opposite to the last one, places the layers for an object formation. 4. The building system performs the material through force, heat or steam toward either remodeling or malformation, mainly using axial or surface movement [8].

In 2008, the applying of digital fabrication in Brazil was still restricted and probably there were little technical uses due to high equipment cost as well as inputs. Another important aspect was the working force qualification into the handling of such equipment, besides higher education made little use of those machines for the design development [9]. Currently, the digital fabrication process seems to have great building potential thanks to equipment and available technology. A professor at the University of Brasília [10] mentions the existence of complex building production equipment in Brazil, also that some of them can be found in some products; the use of that technology is starting to impact little pieces such as art pieces with scales and structures.

In the mentioned scenario where we described briefly some aspects of the current digital fabrication context taking into account the Brazilian status, this work aims to analyze and review the literature concerning the proposed issue within the last 10 years.

2. Method

The research was carried out in the second semester of 2014 through the registered article WebWilson system at the library of USP - University of São Paulo, furthermore the databank of Cumincad which gathers articles related to Computer Aided Architectural Design and works of main events of the theme such as ACADIA, ASCAAD, CAADRIA, eCAADe, SiGraDi and CAAD futures. The keywords were
Digital Fabrication, Design for Production and CAD/CAM for architecture. The search has looked for articles published from 2004 to 2014. After that, it was analyzed the title, keywords and abstracts verifying the link with the research. After this selection, the articles were read, tabulated and categorized according to the following criteria; 275 works comprised the sample:

- Data of author identification: name, university, country and hemisphere;
- Publishing data: journals, magazines, book and thesis, title and year;
- Debating area: teaching, design, buildings and research;
- Scale: object / body, furniture / pavilion, building / construction and urban;
- Type: theoretical / critical, parametric, geometry, biological, historical patrimony;
- Equipment: Robo (3D), Laser Cutting (2D), CNC miling (3D).

The analysis was divided in three topics:

1. **Topic 1** refers to the general literature context with the approach on digital fabrication identifying the quantity data, the working types in which the scale objects and others are produced. Topic 2 debates the architectural design process, also digital fabrication dividing it in 4 blocks for analysis under the tendencies of the contemporary debates. Topic 3 reflects the Brazilian situation in the broad view showing peculiar characteristics of the country. Finally, the works were read and analyzed targeting the current context; besides the ways through which digital fabrication runs.

### 3. Results and Discussions

After presenting how the articles were organized and divided, we show the analysis and discussions below:

#### 3.1. Topic 1 - Identification of Data

This item refers to the identification and contextualization of general literature. From 275 articles which dealt with digital fabrication, 82 (30%) were from North America, 79 (29%) from Europe, 77 (28%) from South America, 29 (11%) from Asia, 4 (1%) from Middle East, 3 (1%) from Africa and 1 (0%) from Central America. 65 South America published articles (84%) were Brazilian productions, 6 (8%) from Chile, 3 (4%) from Argentina, 2 (3%) from Peru and 1 (1%) from Uruguay. This distribution of publications seems to be related to their national events what promoted researchers to write on a daily basis. The highest publishing number was on events summing 197 (71%) works, 64 (23%) of published articles on magazines, and 17 (6%) on books and thesis. The magazines represent the highest publishing on the proposed issue revealing the magazine *International Journal of Architectural Computing* followed by *Automation in Construction* and *PARC_fec.unicamp.br*.

In the articles produced between 2004 and 2014 (Fig.3), we observe the issue has increased in the last 10 years. The highest peak was in 2009 probably referring to the event *Sigradi* which took place in the city of São Paulo making it easier for the Brazilians to take part in the Congress. In addition to that, the necessary machinery
Digital fabrication in Brazil - Academic production in the last decade

for digital fabrication research was more available; this fact enabled its acquisition by the architectural schools justifying the increase in the published work.

Fig.3 Publications per year

We notice that in Brazil (65) and the United States (80) there have been remarks in researches on digital fabrication in the last 10 years, followed by Switzerland (13), Great Britain (13), Australia (12) and Austria (11). In Brazil, UNICAMP takes part in the total number of 29 (44, 6%) of 65 works, almost half of all published works in the country. In the USA, it is remarkable the work at the MIT with 21 (26%). The works present a main debate on digital fabrication and architectural design in 144 (55%); digital fabrication issue is present in 57 (22%) and 17 (7%) which debate digital fabrication and model; 13 (5%) analyze digital fabrication and teaching. These data will be debated in Topic 2.

Concerning the general approach of works, we verified 60% of them were parametric design, 39% were theoretical or critical, 23% debated geometry for architecture, 9% used biological aspects and 2% debated cultural patrimony. From those articles, 15 debated architecture teaching mainly reflecting the needs of digital fabrication inclusion in the syllabuses of the architecture universities. The Brazilian participation flows through the same tendency, such as on parametric designs, teaching, theoretical one and critical works. It is key element to mention the interest on historical patrimony, although less the technologies are broadly used for cataloging, studying of patterns and documentation in architecture.

On the scales of the developed objects, they were categorized by object, furniture and pavilion scale both in buildings and in the urban areas. The most frequent working scales are the two lowest ones; object (32%) and furniture / pavilion (43%). Most works invest on those scales because they are related to the object process what enable it for dimensions and runtime. Another aspect can be due to the size of production machines which probably have a suitable size for a laboratory and not for a building, in fact, laboratories are organized environment at universities. Brazil also
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presents similar characteristics with 46% in object scale and 43% in furniture / pavilion.

The most widely used production equipment are Laser Cutting (2D) and NC (3D) with 123 cases for each; followed by 37 which used 3D Printing and 32 Robo. Laser Cutting use seems to reveal a better ability toward time, also different materials into architectural model construction, and a cheaper equipment cost as mentioned previously.

As aforementioned, Brazil is the country that publishes more articles as far as digital fabrication is concerned, taking part into events it presents an increasingly distribution showing two peaks: in 2009 and in 2014. The main researchers’ concern is toward the design process, having several investigative works of parametric design as well as exploration on digital fabrication. The most common work scales are of body, furniture and pavilion in which laser cutters and CNC cutters were used.

3.2 Architectural Design and Digital Fabrication

The debate on the second thematic topic is on the reading of four tendencies related to the architectural design process which are present in the researched articles, as revealed in the diagram below. For such an analysis, the design process is comprised as it follows: the steps are from the need analysis to the program elaboration, execution and evaluations by users and technicians [11].

Fig. 2 Diagram of analysis

Analysis of block (1): The motivational elements for design elaboration allows us to observe various and several themes: the most common one is the parametric design generally applying the Rhinoceros Grasshopper program, since this tool can be used when associated with subjects like digital fabrication, simulation, modelling, etc. The articles present works with shape and their parametric possibilities associated with design development and digital fabrication. They describe constructive experiences, workshops, furniture and pavilion making; they also reflect digital
fabrication as a tool for the design process; they produce comparative analysis with non-visual programming models and those authors in [12], [13], [14], [15], [16], [17], [18], [19], [20], and [21].

Some works show a concern on the material quality in design development and digital fabrication, that is, designs that make use of wood analyzing its behavior or in the search of materials which have similar behavior to other structures, for example cases [22] and [23]. Geometry has also found visibility among the analyzed issues in the articles. Generally it deals with the object constructability associated with its complex shapes, for example in [24], [25], [26], [27], [28], and [29]. Some other issues which are less frequent are participation, mapping, historical patrimony, reverse engineering, artificial life and simulations.

Block (2) deals with architectural designs and the planning for digital fabrication. In those cases, the works are focused on the planning for fabrication; this phase is called design for manufacturing, production or automation. It has the focus on the fabrication process from the piece elaboration which will define the proposed shape to the assembling of the site, going through detailing, construction and assembling. In the work for the construction of an exposition basis [30], they describe the work development process as: 1. defining geometry; 2. automated detailing; 3. automated nesting with structure organization, the minimizing of waste, identification; 4. generating NC code for machines that is the final step of the production chain. The works of block 2 have in common the understanding of such phases as a specific production design in which it involves the definition of algorithms for geometry definitions, of detailing that will be translated into the production machine, identification of pieces and assembling. The works in this area are [31], [32], [33], and [34].

The block 3 comprises the set of works addressing customized concepts in mass, production management and manufacturing. Some cases address the Lean concept [35], some others address parametrization toward customized production [36]; computing and automation for industry [37]; technological revising for mass customization [38], among others. In this set of works there are analyses on costs, optimization, and users’ participation along with their experiences [39], [40], and [41].

In the block 4, there are articles addressing architectural designs through production and the privileged data are: machine possibilities, material behavior, characteristics on logistics and assembling. These authors analyze how manufacturing parameters can be integrated to the design process enabling communication in the production process [42], also the analyzed production by tolerance tests, structure and assembling [38]. Interdisciplinary aspects, cooperation, connectivity, besides creative constructions are fundamental issues to the architects. Before the quantity of data – code, modeling, visualization, analysis, and production – it is paramount to consider the management and exchange of data which are in every design process and production in architecture. Industrial collaboration toward problem solution is about real problems, fabrication, logistics as well as assembling [49].

The Brazilian articles which address the development of architectural designs associated with digital fabrication excel in model uses for architectural design
development (26%), in the production process it is found (26%), theoretical ones in (15%), among other frequent debates correlated there are parametric designs and teaching as it will be debated below.

3.3 Topic 3 - Brazilian Context

In a work published in 2008, it is found that there were a few researching registered groups in fast prototyping and/or digital fabrication; one of them has been in Brasília since 2000, one in São Paulo since 2005 and one in Campinas since 2006 [44]. Nowadays, it is known that the reality has changed due to the published works at several universities. In those, we observe digital fabrication is key debate representing the main discussion on the issue as a tool for the architectural design development. As a tool, they debate the use of parametric design, technology under laser cutting and 3D printers, use in cultural patrimony, representation of drawing according to the model, processes of design creation, model roles, building process of furniture and pavilion, sustainable furniture, design based on biological structures, technological use for the analysis of distinguished architectural designs along with simulations of behaviors in structures.

In all researched Brazilian articles, we observe teaching holds a prominent subject within the addressed issues. The issue is addressed as a helping tool in architectural design, in the use of exciting technologies and their approach toward pedagogical understanding; moreover in workshops they are associated with parametric designs and considerations over the creation process, and laboratory assembling at the Brazilian universities. Regarding the theoretical or conceptual articles, literature addresses definitions in [44], [9], and [45], in the state of art in [44], researches on technological park in some Brazilian regions and clarifying the technological park according to the author, furthermore there is enough equipment for the Brazilian civil construction use [46].

Finally, it is important to note some of the works were carried out at the Fundamental School and social areas that use digital fabrication technology as a pedagogical tool, along with teaching; tools which enlarge the cognitive capacities, manuals and development are present in [47], [48]. Although, they are a few, it is relevant to mention these types of efforts have extensive receptivity in the Brazilian territory taking into account it is a vast field of action given the characteristics of the emerging countries.

4. Final Considerations

About the analyzed articles, we conclude that digital fabrication is mainly addressed in North America, Europe and South America, specifically at conference events. There are two peaks of publishing on the issue probably due to Congresses: one in 2009 and another in 2014. The main debated theme in digital fabrication is linked to architectural design in subjects such as parametric design, geometry and biology.
Generally, the developed objects are in body scale, furniture and pavilion, furthermore the most commonly used equipment is for cutting and subtracting. Regarding the works which discuss architectural designs and digital fabrication, there are four blocks of approach: (1) those that use motivational aspects as parametric design, simulations, geometry, participation; (2) those that discuss the design process for production generally by algorithms for problem solution; (3) articles which address the management issue verifying optimization strategies, cost and feasibility; (4) those that develop architectural design through fabrication parameters. Brazil stands out in articles on digital fabrication; besides addressing digital fabrication, there are also fast prototyping used as tool for the architectural design process. Teaching has also been a concern of authors; moreover technologies should be inserted in academic curricula.

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5. References


Tactile models of elements of architectural heritage
From the building scale to the detail

Luisa Félix Dalla Vecchia, Adriane Borda da Silva, Janice Pires, Mônica Veiga, Tâssia Vasconselos and Letícia Borges
Federal University of Pelotas

luisa.vecchia@ufpel.edu.br; {adribord, janicefpires, monica_veiga}@hotmail.com; tassia_arq@gmail.com; le_farias_borges@yahoo.com.br

Abstract. This paper describes the development of three-dimensional models, produced using digital fabrication techniques with the goal of providing a haptic experience of architectural heritage. These models were produced in three different representations: the building as a whole, elements and details. This study first undertakes a process of analysis and the formal decomposition of architectural components to identify basic or simplified elements which make it easier to understand the represented object by touching. The results obtained come from assessment tests of the tactile models as experienced by mainly blind individuals. Secondly, as part of this process, a method of constructing such models is defined. This study facilitates a greater understanding of the relationship between the represented objects (historic buildings) and the tactile models, and provides a technological and discursive basis for future implementation of tactile models in a specific context.

Keywords: tactile models, architectural heritage, digital fabrication, haptic experience.

1 Introduction

This paper describes the production of tactile models, using digital fabrication techniques, aimed at promoting a haptic experience of the architectural heritage of Pelotas City. It is the goal of this study to demonstrate that these models could be made available on site, in the buildings they represent, for the purposes of educational tourism. Furthermore, it will show that the models could also be used in specific educational contexts in schools, fairs and exhibitions. The production of these models is designed specifically for use with the blind, but sighted individuals could also broaden their experience beyond the visual using the models.

An earlier study [1], described the use of tactile models to enhance accessibility to an exhibition of photographs showing a building of heritage interest. The references...
used in that case were mostly from the area of museology, some of which highlight the importance of touching.

Neves [2], for example, points out that the brain interprets what we see, and therefore what our brain “sees” does not necessarily reflect accurately the image which came in through the retina. Thus, this author considers the possibility of “seeing” (meaning understanding images) through other senses by adding verbal and tactile means of interpretation.

Teshima [3] describes the development of didactic three-dimensional materials for blind individuals. According to him, the key for developing materials that can enrich the universe of observation through touch is to produce models that the visually impaired have never touched before. The author divides these models into two categories: (i) objects that we cannot touch in actual size, huge or microscopic objects; (ii) objects that cannot exist naturally, they are based on an abstract idea like mathematics, curved surfaces for example.

Although digital fabrication technologies make the production of these models easier, it is important for the objects to be understandable by touching. Therefore, some guidelines need to be considered in the design of this tactile interface. These include making the object’s form simple or braking it up into parts that can be fitted together. According to Teshima [3], it is not enough to make the 3d models; “we need to use our brains to make models which are suitable for visually handicapped persons to touch”.

Physical models play the role of tactile media, and often more than one model of the same object is necessary for a tactile comprehension of it. Therefore, the idea of drawing from the cinematographic scenes described by Bernardet [4] is reviewed in an attempt to achieve a fluid communication between the different models that build up a specific object.

Sarraf [5] considers that visual communication is losing its capacity of seduction; thus, he developed a communication theory using the five senses in cultural spaces. For this author, sensorial communication is key for the democratization of cultural and artistic heritage.

In the context of architectural heritage, we can consider the city as a cultural space which preserves historically relevant buildings for which public access and awareness must be made more democratic. Considering the cases outlined by Teshima [3], these historic buildings can be sorted into the first case: huge objects. Although the buildings can be touched, their form cannot be perceived by touching the object in actual size. Thus, the production of models of these buildings in reduced scale can provide a more comprehensive tactile experience. Furthermore, the fascination produced by these models is evident in people of all ages, thus bringing valuable attention to the architectural heritage of the city.

The importance of the tactile experience is currently highlighted in the field of architectural research, reinforcing the value of the multi-sensorial experience. Herssens and Heylighen [6] state that our experience with architecture is of a multi-sensory nature, that its appearance is important, but its feel, smell and sound also contribute to our experience. However, touching in order to achieve greater
understanding of the elements of an exemplary piece of architectural heritage is often not possible due to the scale of the structure, the inaccessibility of its location or by its fragility. These authors consider that, in the context of architecture, the term “haptic” has a broader meaning than “tactile” because it involves not only cutaneous perception but also the perception of positioning, balance and movement in the built space.

Vermeersch and Heylighen [7] consider haptic perception to be a combination of tactile and kinaesthetic perceptions. Tactile perception interprets the variation in stimuli to the skin allowing us to perceive, for example, the texture of materials. Kinaesthetic perception informs through static and dynamic body postures, for example, an impression of length perceived through the relative distance between fingers. Haptic tools, according to these authors, are tools developed to provide the brain with information through the skin and muscles of the hands.

Another important aspect of this paper refers to technological matters. Many of the digital models of architectural heritage produced to date in this context were made for use in virtual reality and web viewing as static images or animations. Therefore, these models considered the possibilities of optimizing the representation of textures through the use of images. They do not have a corresponding geometry that can promote comprehension of an object through touching. The initial processes regarding the use of 3D printing techniques available in this context (additive process of plastic layer deposition) are described in [8]. Later, laser cutting also became available in this context of study, broadening the possibilities of digital fabrication. This led to a comparison between the two techniques for the production of models of several elements of architectural heritage, in particular metal railings. Thus, this study has as a starting point a recognition of the technological limits such as dimensions imposed by the machines available and the limitations of the techniques themselves, identified in these initial studies.

The architectural heritage represented is of eclectic style, rich in complex ornamentation. Several authors such as [9], [10] and [11] write about these buildings and strive to understand and explain the meaning of each element. However, very little appears in their works regarding a more detailed study of the geometrical aspects of this architecture, especially considering theories which make it possible to relate each one of the parts in a composition to the whole. Such theories could explain the logic of the facades and make the process of representation easier.

2 Materials and Methods

This research was divided into four stages:
Stage 1: Bibliographical review, identifying an interdisciplinary field according to the research examined in the previous section.
Stage 2: Establishment of a trial-theory for the production of the tactile models. This trial-theory was based on the bibliographic review and on the previous experience of the authors [1]. In this previous experiment a method was developed for the production of tactile models specifically to enhance the accessibility of an exhibition
of photographs of an industrial building. This method employed the “gradual addition of information”. Therefore, the second stage of this study involves transposing our method, not from photographs but through the tactile models related directly to the three dimensional object. This stage includes the geometric analysis of the buildings, taking into consideration the meaning of each of their elements in the context of architectural history. The transposition of the method required planning of the decomposition and recomposition of the represented element and the production of models in several scales. This process is described for each object included in this study in section 3.

The selection of the elements of architectural heritage to be represented in this study was influenced by three main factors: the potential of the object to broaden the group’s understanding of the fabrication techniques available in this study context; the existence of a previous digital model of the object produced for virtual reality; and the interest in generating information about buildings belonging to the University in which this study takes place.

Figure 1 shows the buildings chosen for this study named as Case 1, 2 and 3. Only the building in Case 2 does not belong to the University, but rather to the municipality. However, it was chosen for this study due to its importance to the city and a recent partnership between the municipality and the University aimed at promoting the architectural heritage of the city through tourism, education and cultural initiatives.

Fig. 1. The three buildings chosen for the study

Stage 3: In this stage the experiment was carried out by a team of professionals from a range of disciplines including occupational therapy, architecture and broadcasting.

After the analysis of the data collected in the experiments with the tactile models for the photographs, a brainstorm exercise was carried out in order to transpose, in a critical manner, the gradual addition of information. In this process, the need to have a more fluid transition between the layers of information was identified, which led to a search for new references and to the hypothesis that cinematographic language could contribute to this process. Thus, the method of gradual addition of information was re-interpreted. The framing of the camera defines each one of the three-dimensional models as the scene of a layer of information, while the zoom movement of the lens defines the detail of this information, determining the scale of the model,
either to explain the location, the overall form of the building or each one of its components.

Personal perception was also examined during this brainstorm process, as a factor that would affect how accurately the models would be decoded. Testing the models with a blindfolded sighted person was suggested as a possible means to measure the precision of the development of the models. First the experiment would be carried out blindfolded, and then the blindfold would be taken off. This would make it possible to determine whether the mental image created by the models matched the actual 3D model.

Stage 4: In this stage conclusions are drawn about the results of the experiments, and proposals made to systemize the production of models as a means to continue the representation of the architectural heritage in question.

3 The Production of Tactile Models: Analysis, Formal Decomposition and Recomposition

The architectural elements represented for each case of this study, a dome, a balcony and metal railings, had been previously modeled for the production of photorealistic images, animations, real time viewing and anamorphic images [12]. These models were taken as a starting point for the production of the tactile models.

3.1 Case 1: From the Representation of the Dome to the Building

The dome of the building (Figure 2), characterized as Case 1 in the context of this study, is one of the most popular elements of architectural heritage in Pelotas. This building, called Grande Hotel, is characterized by its eclectic style with Art Nouveau influence. It was designed by the civil engineer Theóphilo Borges de Barros and built between 1925 and 1928 [9], it was a hotel and also a casino and is currently being restored to be a teaching hotel.

The digital model of the dome, which was initially used in this study, was produced as a didactic activity in a graduate course (image on the left in Figure 2). The first model in 3D printing of this element was produced during the process of analysis of the compatibility of the existing model with the digital fabrication technology available.
The model had been made mainly for obtaining static images and, therefore, presented several problems for use with 3D printing such as overlapping elements and a very high number of polygons. These problems were fixed and some parts were even re-modeled to allow the 3D printing of the dome shown in the middle image of Figure 2. It is possible to observe that there were some problems with the printing of some complex elements due to the reduction in scale. The studies, at this point, were aimed at understanding the limits of the technology available considering complex geometries and compatible scale. At this point the studies did not yet consider the need to understand the model by touching. The image on the right in Figure 2 demonstrates the solution of breaking up the digital model for printing, which sought only to solve the problem of resolution of the model, and not the quality of tactile information that it could offer.

In order to apply the method of gradual addition of information, the modeling process was analyzed, decomposing the form and identifying its basic elements. Figure 3 illustrates the modeling process, highlighting the rule of cyclic symmetry, which helps in understanding the form of the dome.

Given the need to produce models of the building as a whole, and in particular to focus on the relative position of the elements on the facade, an analytical study was carried out of the geometric aspect of the exterior form of the building. Figure 4 shows an example of the kind of analysis carried out showing implicit geometric figures such as rectangles with the golden ratio and square root ratio, both very common in buildings of that era. This analysis also contributed to the description of
these facades regarding the position of each element, and suggested a logical sequence for the addition of information.

![Fig. 4. Geometric studies of the main facade of the building of case 1.](image)

Figure 5 shows, in the first line, part of the plan for producing the models of Case 1 taking into consideration the scale and how much detail to include in each model. The second line in Figure 5 shows the tactile models produced, from left to right: the location of the buildings of Cases 1 and 3; a simplified model of the building, which allows whoever is touching it to understand the overall shape of the building, the number of floors, the position of the dome, and the shapes and number of the windows; the dome in a larger scale with all its ornaments: this model lets us identify, by touching, the relative position between the elements of the dome as well as its shape. The fourth model is of one of the windows of the dome in a larger scale to allow a better understanding of its form and how it fits onto the body of the dome; the fifth model is of the crown of the dome in a larger scale allowing a better understanding of each one of its elements. This model was also produced in two formats of separate pieces for assembling (sixth and seventh images) in order to explain the underlying rules of the geometric form.

![Fig. 5. Planning of the models and models made for case 1.](image)

### 3.2 Case 2: From the Representation of a Balcony to the Building

The building in Case 2 is of a classic eclectic style with colonial and baroque influences [9]. It was built before 1830 in colonial style and was renovated between 1875 and 1880 when José Antonio Moreira, the Baron of Butuí, hired the architect Isella Merote to renovate the house in the eclectic style already present in the neighboring houses. Currently, it has on its ground floor the House of Culture Adail Bento Costa and the city's Office of Culture on the second floor.
Fig. 6. Photographs of the building of case 2 and digital models of the balcony.

The digital model of this element (image on the right in Figure 6), initially used for this study, resulted from an exercise developed in the same context as the first model of Case 1. The third image in Figure 6 illustrates one of the steps in the modeling process, which shows the study of each element, identifying the logic in composition by using symmetry procedures, translation, reflection and rotation.

For the 3D printing of this model it was also necessary to correct several problems as in Case 1. In order to do so, most of it had to be modeled again. The thinness of its components (0.5cm in natural scale) and the fact that they present a curved surface caused problems for printing the balcony in a convenient scale as shown in Figure 7. To achieve the shape of the balcony shown on the image on the right, it was necessary to also use manual techniques and the model was still too fragile. Currently, further experiments are being carried out to find alternatives using this same technology, and further experiments are being planned for the use of laser cutting, taking advantage of the experience acquired with Case 3.

Fig. 7. Problems faced in 3D printing the balcony [8].

As in Case 1, an analytical study was carried out regarding the geometric aspects of the exterior form of the building, taking into account the need to produce models of the whole building. The aim of this analysis was to guide the process of production of the tactile models using the method of gradual addition of information.

3.3 Case 3: From the Representation of Railings to the Building.

The building in case 3 is of classic eclectic style with colonial and Baroque elements. It was built between 1884 and 1889 and belonged to the senator Joaquim Assumpção. It was gradually changed according to the family’s financial condition [9]. Members of this family lived there until 2005 when it was sold to the university (UFPel) and became an administrative building.
Tactile models of elements of architectural heritage: from the building scale to the detail

Figure 8 shows the main facade of the building and the two railings used in this study. These elements had been previously analyzed and digitally modeled in an undergraduate context.

The railings on the wooden door was printed several times to evaluate the parameters both for modeling and for printing, considering the need for the model to have handling resistance, however, a suitable model could not be achieved. The search for alternatives led to the hypothesis that laser cutting would be suitable for the production of these models in order to achieve handling resistance.

Figure 9 shows the railing from the wooden door represented in a single model and also in separate portions. These parts of the railing are used as puzzle to demonstrate the implicit geometry such as regulating rectangles. These rectangles of specific proportions are laser marked so that each one can be recognized by touching. As in the previous cases, a geometric analysis of the facades was carried out to guide the study of the building as a whole.

4 Experimentation With the Tactile Models Produced

Up to this moment, the experiments were carried out with the models produced for case 1. In the current stage of investigation, the experiments were focused only in observing the capacity of the models produced in informing specifically the geometric form of the architectural heritage represented. It was the goal of these experiments to evaluate the relevance of each layer of information with its proposed “framing” and level of “zoom”. Two volunteers took part in the experiments: the first, experiment 1,
was carried out with a blind individual and the second, experiment 2, was carried out with a sighted individual, according to what was proposed and explained in section 2.

4.1 Experiment 1

The first experiment, was carried out with a blind volunteer of 21 years of age who started losing his sight at the age of 12 and was completely blind by 16. This volunteer has a visual memory, however, he only recently moved to this city and, therefore, has never seen the building of case 1.

The first model experienced by the volunteer was that of the building as a whole with simplified shapes on the facades (second image on the second line in figure 5). As he explored the model with his hands he started saying that he could understand it well. He identified the number of floors in the building, the difference in shape between the windows, he identified the location of the dome and its windows saying that he could make a good mental image of what the building is like.

The models touched next were those of the crown of the dome in a larger scale, both the one of the whole crown as well as the ones meant for assembling the crown (the last three images in figure 5). In his opinion, only the crown as a whole is already enough to perceive the shapes that build it up. The model made up of several pieces of the elements of the crown (last image in figure 5), was very confusing. The model in which a slice of the crown fits in with all the rest of the crown helped to notice how the shapes repeat themselves.

The next model to be handled was the one of the dome. The volunteer indicated that he had already noticed the number of windows and their position in the model of the building, indicating a redundancy in the information. However, this model was important to provoke the perception of more details in the windows and crown, to complement the connection with the larger models of these elements. In the sequence, while handling the larger model of the dome’s window he noticed the square shapes formed by the railings on the window and asked if the other windows in the building were also like this (they are not). In this case, the need of other framings was noticed, such as the one planned to show a section of the facade.

Lastly, the model of the location of the building with its surroundings showed to be problematic. The volunteer considered that it would be better to identify the streets by a single continuous line, interrupted only by the name in braille.

4.2 Experiment 2

In this second experiment there was the purpose of observing the performance of the same models used in experiment 1, however, with a sighted person, initially blindfolded. This volunteer is a 28 year old woman who was born and currently lives in Pelotas and often walks past the building. Before the experience started she was informed about which building the representations were of.
The first model handled was one of the seven volutes of the dome’s crown, with the intention of starting from the basic elements of information to explain the composition. Her reaction was an attempt to associate the element to the geometry of metal railings. As she touched the following model (crown with a removable slice) the volunteer stated that she could understand how the crown is composed. She put both pieces together and identified the object. The third model (of the crown in one piece) didn’t add any relevant information, since the form had already been comprehended through the previous models.

The next model presented was the model of the dome which allowed the volunteer to notice how the windows were positioned. As she handled the model of the dome’s window she stated never having noticed that he top of the window was thicker than the bottom, but that this made sense given the curved surface of the dome. In handling the next model, of the building, the volunteer was surprised to notice that the windows had different shapes, she had never noticed this difference.

The last model was the one of the location and, in this case, it was necessary to guide the volunteer’s fingers explaining that the lines represented the curb of the streets. She asked the name of the streets and recognized the location.

Following this, the blindfold was removed and the volunteer expressed a great fascination by the models, continuing with the haptic experience, realizing the pleasure in handling the models, incremented by the visual experience. For her, the mental image created of the models was very close to the vision she had of the models after taking off the blindfold.

5 Results and Discussion

The results have encouraged us to continue and intensify the investment in the production of the models. Partnerships are being established with public and museum institutions to use the representations produced so far.

The method based on analysis, deconstruction and reconstruction of the form, allowed the information to be made available by layers, broadening the knowledge about the architectural heritage represented both for sighted and blind individuals. The formal relations of the buildings should be broadened with the use of the models from case 3 making the matters of proportion more explicit.

Even when the visual experience is possible, the haptic experience proved to be very positive in bringing closer elements that are too far to be noticed as well as allowing a different perception from the usual visual on site experience. Touching highlighted certain aspects of the architectural heritage involved which often go unnoticed.

The absence of the planned model of a section of the facade of case 1 which should bring the ornaments, proved to be relevant since such model could have helped in the perception of the historic period of the building especially by blind individuals. It was also noticed that the order in which the models were handled did not influence the comprehension about the architectural elements represented as long as the models were accompanied by the description of each model.
For the comprehension of the overall shape of the building, the place of the elements in the building as well as its formal aspects, the models in 3D printing by plastic deposition showed to be adequate. However, for very thin elements such as the metal railings, a stronger material is necessary and, thus, the laser cutting allowed these models to have handling resistance.

On a technological point of view, for the specific context in which this study is inserted, the experiments of production of such models from digital fabrication techniques has promoted the diffusion and acknowledgement of this technology.

6 Final Considerations

It is considered that the study achieved its goal of producing tactile models that can give information about the architectural heritage involved to blind individuals and add information to sighted individuals. However, it is important to consider that it is the intention of this study to add further geometrical and historic information with the models that are still to be tested.

The experiments carried out so far have proved to be very useful indicating several improvements to be made on the models. Further testing with individuals with different cultural levels regarding the heritage involved and with different visual abilities (individuals born blind for example) will make it possible to produce the models to reach the widest variety of profiles possible.

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Analysis and validation of the digital chain relating to architectural design process
Achievement of a folded structure composed of wood panels

J. Meyer, G. Duchanois and J.C. Bignon
School of Architecture of Nancy
(meyer,duchanois,bignon)@crai.archi.fr

Abstract. The research presented in this paper revolves around the experimental development of the morpho-structural potential of folded architectural structures made of wood. The aims are to develop an innovative system for timber used in sustainable construction and to increase the inventory of wood architectural tectonics. First, this article provides a characterization of the digital chain associated to the development of non-standard folded structures consisting of wood panels. The purpose is to study the architectural design process from parametric modeling (through CNC machining) and assembly operations to production by way of a full-scale experimental pavilion. Secondly, a number of analytical experiments have been performed towards the completion of the pavilion, in order to validate the design process.

Keywords: Architecture, folded structure, robotic fabrication, computational design, parametric modeling, wood panels.

1 Introduction

The term “fold” as used in the field of architecture shows a shift in the designs and vocabularies of contemporary forms. For example, Peter Eisenman has used, for the Rebstockpark project, the fold as a concept of changing forms continuously through time [1] or even Rem Koolhaas for his work on the "trajectory" where folds generate more singularities [2]. The fold is partly based on the theoretical foundations of the philosopher Gilles Deleuze, in which the traditional form and its material relation as a spatial mold, has given way to “a continuous variation of matter as a continuous development of form” [3]. The designed architectural object, takes place in an evolutionary continuum where the parameter variation replaces the constant laws. The “event object” with vast potentials and modulation possibilities is replacing the traditional “fixed monument object”. The fold as a process means an adaptive formalization mechanism. Henceforth, the fold is becoming a conceptual tool to address the realm of contexts and perspectives in architecture.
The practices of digital technology as developed today in the field of architectural design and manufacture have instrumented the idea of a continuous development of the shape. This practice has spread the idea of fold to the production process. The chronological chain, from design to manufacturing, is no longer linear but becomes a series of simultaneous developments and possible variations. As the philosophical concept can operate as an architectural one, the fold becomes a productive concept that can be explored. The emergence of new materials or new components and their relating technicalities makes possible this continuum of shape (de)formation and virtualization on a basis of potential variations of the production tools. It aims, although to a limited extent, is to focus on the fold with respect to its morpho-geometrical dimension and its ability to respond to a fluctuation of contexts and uses. The fold brings a fresh look on the integration of the structural dimension as a modulation factor and allows adaptive modeling within the design-manufacturing continuum. Finally, we report on an experiment leading to the production of a folded structural envelope made of laminated wood panels.

2 The fold

2.1 The fold: a Morpho-structural system

In nature the fold can adapt to local stresses and external forces which will lead to a deformation of the material. The fold can suffer a deformation as in the case of geological folds characterized by orogenesis. It may also be a shaping genetically adapted like palm leaves which fold is formed during the growth cycle to provide it with wind resistance. Generally, the fold provides rigidity while minimizing the material used. For example, we find that this logic of resistance in the field of stamped metal sheet technology is used in the automotive, aerospace and general engineering industrial sectors. In architecture the fold provides many morphological but also structural possibilities. It brings rigidity and inertia as required for the structural stability of the architectural works adopting it. Moreover, by principle, the fold highlights an efficient relationship between the projected area and the material quantity required for the construction. The saving made on the material gives a real environmental dimension to the fold. In addition to the conceptual dimension mentioned in the introduction, the fold provides a genuine tectonics in architecture. This leads to a visual evidence superposing both the clarity of a plastic form, and veracity of a construction design [4] benchmarked against the material and structural dimension of the designed shape. The characteristics of the fold define a language; a source of architectural and structural motion [5].
2.2 The folded material

From a physical point of view, every material can theoretically be folded. But from the viscous to the rigid substance, the folding can result in stress efforts specific to each matter. We can classify a fold by continuity or discontinuity of material.

The continuous material. The fold is commonly associated with the deformation of a thin material surface with a small bend radius regarding the thickness of the material (metal foil, paper, fabrics ...) but it can also be obtained by means of molding technologies. A bending action, which consist to roll back the material according to a determined angle, introduces internal stresses of traction/compression and causes a reduction of material thickness. Mathematically, it is estimated that the tangents at a point of the surface are continuous in all directions. In that case, we can define a minimum acceptable bend radius before the material breaks. Materials with plastic dimension have a maximum degree of deformation. This plastic deformation gives limits to bending radius. However, the disadvantage of this technique lies in its inability to produce big structures.

The discontinuous material. A fold can be accepted as a union of different surfaces. Mathematically it can be defined by the discontinuity of tangents to a point of a surface and in a given direction. The one-time change of direction in physics means an interruption of matter and thus the notion of assembly. A classification of assembly types must be appropriate to the material in use, to ensure continuity of internal its forces. This third method interests us regarding its use on industrial wood panels.

3 Fold and Folding models

Our research turns to the use of flat industrial panels for the developing folded wood structures. Currently, an insufficient mastership of the physical wood behavior laws to make panels deformable has not yet allowed an easy use of the material. Hence, we orientate our work towards a technology of assembled folds.

3.1 Study corpus

Applied initially to walls or roofs, folded structures quickly evolve towards arch, portal frame or folded shell. The first two projects present folding structures with
continuous material. The UNESCO concrete building in Paris by P.L. Nervi reconnects the dialogue between form and structure [6]. The architectural realization “Corogami Folding Hut” by David Penner reveals folds generated by mechanical bending action in order to obtain a sufficient rigidity [7]. In the environment of wood material several experimental achievements have demonstrated the high potentials of wood assemblies to create particularly inventive architectural design. The pavilion designed by Hybrid Space Lab office in Berlin, consists of triangular plywood sheets sewn together with cable ties [8]. The Thannhausen Music Hall in Germany designed by architect Regina Schineis, shows a regular folding ensuring a portal frame system fixed to a concrete slab [9]. The temporary pavilion in Osaka realized by Ryuichi Ashizawa Architects [10] and the Chapel of St Loup in Pompaples [11] attest wooden folded structures virtues by their structural and architectural qualities. Oriented monodirectionally folds increase the stiffness of thin surfaces. Structurally, these constructions work as a series of portal frames. The Japanese pavilion is equipped with a primary skeleton creating ridge and valley edges and covered of panels in a wind bracing way. Quite the contrary, the chapel wood panels ensure both the architectural envelope and the structural system. Laminated timber panels associated with a "digital production line" approach have opened up new perspectives for the building industry in creating prefabricated wooden structures. Timber panels like cross-laminated timber (CLT), or laminated veneer lumber (LVL) introduce specific features like their availability on large sizes or their high strength even for thin panels. While traditional timber-frame structures use timber panels only for cladding and cross-bracing of beams, new typologies such as Timber Folded Plates use plate-assemblies as load-bearing structures (i.e. Interlocking Folded Plate Structure) [12].

![Fig. 2. Interlocking Folded Plate Structure (left) and The Temporary Pavilion (right)](image)

### 3.2 The fold model

The fold is the unit element of the folding. It consists of two entities called "faces". As part of our work on folded architectural structures made of wood panels, we consider only planar faces. The combination of two faces at a common edge and to the appropriate non-zero angular value, creates geometrically a fold. It is characterized by the notion of amplitude (height of the fold defining its inertia) and the concept of frequency (base of the fold). Folding is the combination of several folds.
3.3 The folding model

Architectural typologies concern continuous covering envelopes (vaults) or revolving forms which interest lies in their inherent stability (dome). The shape of the envelope, as defined by architectural criteria, represents the basis of fold modeling. The use of flat panels leads to the creation of break lines during the generation of the folded envelope. These break lines discretize the support skin in planar surfaces matching with the curvilinear morphology of the initial envelope. The fold is then oriented in relation to the normal of the envelope surfaces; it is controlled by parameters of frequency and amplitude of the fold. The folding method defines the disposition rules of peaks and valleys edges according to the normal of the face. Pilot criteria based on the material, structural behavior and manufacturing techniques are associated to these parameters. The choice of material interacts with the rigidity (Young's modulus), thickness of the panels (changing the assembly by nature, reacting to the weight), and the dimensioning of raw panels (modifying the pattern layout and size of the panels). The structural validity is generated by an analysis software that impacts stiffness, folding inertia (controlling amplitude and frequency), and stability (modifying the break lines, assembly stiffness). The manufacturing imposes geometric constraints derived from a Numerical-Control tool parameter settings, such as angular cuts and maximum panel size (weight and size management). Finally, it makes sense to set up a management system monitoring the kinematic impact to verify the feasibility and accuracy of the assembly parameters. The architectural validation will be established by the designer.

4 Digital fold

The current state of the digital chain as proposed in our work consists of a parametric design phase of morpho-structural envelopes associated to a robotics manufacturing phase. The digital design environment is composed by the modeler Rhinoceros coupled to Grasshopper (editor of graphic algorithm for parametric geometric data management) and the finite elements analysis software Cast3M for structural verification. The digital production environment is organized according to the Computer Numerical Control (CNC) machine used.
Analysis and validation of the digital chain relating to architectural design process - Achievement of a folded structure composed of wood panels

4.1 Parametric design

The digital continuum is ensured by the creation of clusters so as to generate different command codes. This digital model does not define an optimal solution but is sufficient. Those parameters allow the architectural folded shapes to match as much as possible the satisfactory structural features without deviating from the morphology of the initial envelope.

Shape Parameters. The "envelope support" is defined by a Nurbs typed curvilinear surface. These envelopes are characterized by two directions. The first enables a discretization of the initial envelope into a number of configurable break lines, and the second corresponds to the folding orientation. The folding algorithm determines a regular or an irregular grid. It can manage the fold's amplitude by using the normal vector of the faces alternated positively or negatively. The frequency and amplitude parameters are managed through a table of values. The creation of the fold generates two panels of 4 non-coplanar edges; a VBnet script allows the determination of surface flatness with a variable degree of precision. The structure thus adapts to the deformation capacity of the material which requires pre-stressed panels for mounting.
Assembly parameters. When applied to wood structures, each panel has to be assembled. The assembly is defined by the number of degrees of freedom (lineal pivot), as well as by a specific joint method (dovetail joints). The choice of the number of degrees of freedom for stability verification is imposed on us. The modeling of timber structures requires to take joint slips in consideration (refer to paragraph 5.2). The technological part of the assembly leads to a specific production level and assembly kinetics. Currently, kinetics of assembly in the digital continuum is not taken into account. Setting the thickness of the surface model reveals a geometric complication which leads to, in most cases, a duplication of nodes. This problem can be tackled by a local construction feature (obviously by connectors...). Nevertheless, this kind of intervention remains manual thus calling for further reflection on the design.

Structural analysis parameters. The introduction of a structural evaluator using the method of shell type finite elements (Cast3M) enables the validation of stability of the structure and its dimensioning. The meshing (discretized geometry), the materials and the limited kinematic (supports) and static (loads) conditions are commanded by specific clusters (Grasshopper). The structural fold gives inertia to the envelope, brings stiffness to big surfaces with a minimum of material, and stabilizes the structure through three-dimensional combinations. These three mechanic principles of the fold are considered to be the evaluation criteria for structural envelopes. Although the structural analysis has not yet led to automatic modifications effected on the envelope morphology thus data has to be treated manually as a means to interact with the different parameters set out in the morphological modeler.

4.2 Digital manufacturing

The machining methodology depends directly on the characteristics of the tools used (admissible size of raw wood panels, characteristics of cutting tools, methodology of clamping system, ...) and of the material (nature of the material, ...). These characteristics make it possible to define the pattern layout of different elements comprising the folded structures. This layout takes into consideration the management of woodgrain and off-cuts to achieve structural optimization. The model integrates an algorithm that numbers the pieces and examines the different elements from all angles by a grid pattern defined on a two-dimensional plan. At this stage, the numeric
command necessitates the writing of command lines to enable the generation of tool paths in order to cut pieces according to the pattern layout made beforehand.

5 Experimental fold

The purpose of this experiment is to validate the accuracy of the parameters implemented in the design phase as well as the correctness of the implementation. The experiment takes place against the backdrop of an exhibition known as the “Wood Challenges” [13], where the inventive capacities of wood to deal with architectural, technical, economic and environmental issues of today and tomorrow are demonstrated. This "welcome pavilion" (L=8m; l=5m; h=4m) has been created to test the digital chain of computer design to digital manufacturing.

The envelope support was folded according to the morphological criteria as required by the designer and coupled to the parameters of the material (laminated wood panels 10500mm x 1800mm x 40mm) and those of the CNC machine tool (5 axes CNC Güdel machine, figure 4a) put at our disposal as well as the parameters set out from the structural analysis. A dovetail connection system was chosen to process the folding edges and a tongue-and-groove system was adopted to join the panels along the break lines. In order to distribute the structural forces more evenly, a compression ring was added. This type of piece requires manual intervention in the computer model. The digital manufacturing requires several data transfer formats. A STEP standard was used in order to achieve the data transfer from Grasshopper to Lignocam; a BTL standard, provided by Lignocam, is particularly interesting since it takes into account the specifics of wood process; for example, a half lap on a piece extremity cannot be machined in the same way as a longitudinal process. Finally the trajectories generated by Lignocam are transferred to Woodlex gantry thanks to LIE and ABB Robo-studio. The different data exchange formats (STEP, BTL, ISO and RAPID) evidence a risk of breakdown in the continuity of the digital chain.

The production process included the cutting and machining of 57 wood pieces. The problematic of raw panel constrains a specific clamping method needing a double positioning of wood pieces. So clamping system has been divided into two steps. First, a nesting procedure is necessary before placing drillings over the raw timber panel in order to locate the pre-machined items at their correct position. After doing
so, each pre-milled panel is finished and a mounting test is performed at the workshop in order to check the installation kinematics and joint gaps.

**Fig. 8. Digital device of manufacturing and Assembled structure.**

### 5.1 Characteristics of assemblies

**Technological choice of connections.** A twisted dovetail joint might be sufficient for assembling the structure [14]. However, the assembling kinematics selected, linked to the difficulty of handling such heavy panels, required the use of two different joints; the dovetail defined in the project does not allow a complete panel blockage, so a tongue and groove system was used to lock each panel.

**Fig. 9. Woodworking joints**

**Structural characterization of connections.** Each assembly is defined by a junction family (dovetail, tongue and groove, ...). A parametric and geometrical definition of assemblies in Grasshopper software allows the manufacturing of these assemblies. The assembly is modeled by its connection type (linear pivot) in a finite elements shell type software (CAST3M). Each assembly is represented by a coupling of different degrees of freedom (3 translations and 3 rotations) and is defined by the stiffness corresponding to the joint slip (1 joint slip per degree of freedom). This coupling is implemented in the finite element analysis software by a stiffness behavior associated to its technological landmark.
Analysis and validation of the digital chain relating to architectural design process - Achievement of a folded structure composed of wood panels

5.2 Morphological and structural validation

The morphological analysis is done in two steps. Firstly, the morphological analysis helps validating the lassergrammetry work performed on the piece after milling it, giving us information about the dimensional error in percentage between the numerically modeled piece, and the processing panel piece (5%). This error is due to a lack of precision in the robot’s movements and also the positioning of the tool holder. Secondly, the analysis is to validate the assembling methodology with the complete use of lasergrammetry for structure assembly, so as to analyze the morpho-structural impact of dimensional deviations on each assembled element (average precision 1/1000). These errors are the result of an incomplete imaging linked to the scanner, manual cleaning of specks and spots, scanner precision and hygrometrical behavior of the material used. By examining the tolerances in traditional wood construction, we find this to be an exceptionally low value. This precision fulfills the necessary and sufficient conditions for the machining precision process to be validated and the assembly protocol confirmed.

The experiment is to replicates the effects of a specific vertical load and the effect of wind on the structure by lateral traction. To identify the structure's experimental stiffness (Ks), the displacement ratio of structural nodes was measured by using mechanical sensors and lasergrammetry devices.

The structural validation is performed through backward reasoning. In order to adjust the joint slip variable in the numerical model the conditions of the experiment were simulated in the finite shell elements calculation software (CASTEM).
Parameters concern elastic properties of the material (Young’s modulus for dry wood) and the stiffness of assemblies. These, define a relaxation of the degrees of freedom, as well as the internal joint slip of the assemblies (relative movements between two assembled pieces). To confirm the correctness of the parameters, we compared the overall digital behavior of the structure with the results of the experiment. The elastic behavior obtained during the loading phase corresponds to a structural accommodation cycle. Analysis and experimentation thus rest on the stiffness obtained during unloading, which becomes purely elastic. At the same time, this experimental loading was simulated on finite elements calculation software to define a digital elastic stiffness of the structure (Ks) depending on joint slip according to an assembly stiffness (Ka) with an enterprise value of zero to (+) infinity. Against the data obtained from the calculation software, the digital model of a perfect assembly is ten times superior to the experimental value found. It is therefore necessary to take assembly shifting into account. It can be stated that the assemblies correspond to a lineal pivot coupled to stiffness [15]. Experimental structural stiffness obtained by unloading is plotted on the curve (Ks as function of Ka) to define the assembly stiffness of the folded structure. The value of the stiffness obtained is relatively low. This is due to high humidity present in the wood panels. Important work on assemblies still needs to be done. By playing with different assembly typologies and technologies (connectors, gluing, etc.), the stability of structures can be increased.

6 Conclusion

The fold is part of the new architectural design languages. The digital dimension participates actively in this morphological quest and is today a basic of architectural research. In our work, we tried to outline a first numeric controlled design tool whereby the folded structures under study are considered to be architectural "objectiles" [16]. Technical variables (structural analysis, manufacturing, erecting and materiological) integrate the architectural design genesis. In the context of the fold as a formalization process, these variables lead to a geometrical fold (re)configuration in order to find an acceptable form.

Nevertheless, the numeric continuum is incomplete. Several actions require a manual intervention, notably in the return of results of the structural analysis, data
management of the tooling and the installation phase. The experiment, as conducted, allows us to validate our digital design tool and digital manufacture of folded structures made of solid wood panels. This pushes us to further pursue our work in the automatization of geometric correctors and optimization of the digital chain.

One possible perspective of our work consists of developing the assembly by robots. Its usefulness lies in the development of alternative construction techniques ensuring transposition of industrial manufacturing technologies by combining prefabrication and production advantages [17]. Our morphological study on the theme of fold, and its derivative towards folding, is presented as a possible solution to an architectural production assisted by digital technology, as Lynn [18] or even Cache has conceived. The interest of the dynamic flow of morphological genesis with literally complex structures does not lie in the shape obtained, but in the technological process itself. This digital approach, leading to new practices, requires special training in order not to lose the scope of skills acquired previously.

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Migratory movements of Homo Faber
Mapping Fab Labs in Latin America

David M. Sperling¹, Pablo C. Herrera² and Rodrigo Scheeren¹

¹University of Sao Paulo
sperling@sc.usp.br, rodrigoscheeren@gmail.com

²Peruvian University of Applied Sciences
pablo@espaciosdigitales.org

Abstract. The present paper is a mapping study of digital fabrication laboratories in Latin America. It presents and discusses results from a survey with 31 universities’ fab labs, studios and independent initiatives in Latin America. The objective of this study is fourfold: firstly, to draw the cultural, social and economic context of implementation of digital fabrication laboratories in the region; secondly, to synthesize relevant data from correlations between organizational structures, facilities and technologies, activities, types of prototypes, uses and areas of application; thirdly, to draw a network of people and institutions, recovering connections and the genealogy of these fab labs; and fourthly, to present some fab labs that are intertwined with local questions. The results obtained indicate a complex “homo faber” network of initiatives that embraces academic investigations, architectural developments, industry applications, artistic propositions and actions in social processes.

Keywords: digital fabrication, fab labs, Latin America, mapping.
A New machinecraft
A critical evaluation of architectural robots

Cristina Nan
Hafen City University
cristina_nan87@yahoo.com

Abstract. This paper intends to develop an understanding of the new role robotics occupy in the architectural process, from the early stage of conceptualization to the final stage of its materialization. This issue will be addressed on two levels of discourse. While the first level discusses the theoretical-philosophical framework behind the architectural integration of robots, the second investigates the resulting methodological implications on an applied research project. A critical evaluation of the use and the self-development of robots or robotic devices by architects is being aspired to. The attempt to redefine the status of the machine in general, and specifically of the robot, seeks to illustrate the robot as an active design agent.

Keywords: Robotic printing, robotic fabrication, construction strategy, machinecraft.
Formal descriptions of material manipulations
An exploration with cuts and shadows

Benay Gürsoy¹, Iestyn Jowers² and Mine Özkar³

¹Istanbul Bilgi University
benaygursoy@gmail.com

²The Open University
i.r.jowers@open.ac.uk

³Istanbul Technical University
ozkar@itu.edu.tr

Abstract. Shape computation in design is never purely limited to visual aspects and ideally includes material aspects as well. The physicality of designing introduces a wide range of variables for designers to tackle within the design process. We present a simple design exercise realised in four stages where we physically manipulate perforated cardboard sheets as a case to make material variables explicit in the computation. The emphasis is on representing sensory aspects rather than easily quantifiable properties more suitable for simulations. Our explorations demonstrate the use of visual rules to represent actions, variables and form as well as how to control the variables to create new results, both desired and surprising, in materially informed ways.

Keywords: material computing, shape rules, making.
Super-details
Integrated patterns from 3D printing processes to performance-based design

François Leblanc
McGill University
francois.leblanc4@mail.mcgill.ca

Abstract Performance-based architecture has predominately been influenced by computational advances in simulating complex organizations. The advent of 3D printing, however, has introduced a new approach to generate complex forms, which is redirecting focus from shape-centric design to material design, namely, innovative structures and properties generated by the process itself. This article investigated the multiscale approach potential to design using extrusion-based 3D printing techniques that offer novel geometric organizations that conform to desired performance. It was found that 3D printed toolpaths adapted to extrusion-based systems render an anisotropic behavior to the architectural object that is best optimized by designing tessellated surfaces as the primary structural shape from which small-scale periodic surfaces can be embedded within a larger geometric system.

Keywords: 3D printing, multiscale design, extrusion-based systems, porous material, topology, CAD integration.
Architecture meets gaming and robotics
Creating interactive prototypes and digital simulations for architects

Taro Narahara
New Jersey Institute of Technology
narahara@njit.edu

Abstract. This paper presents an approach to producing an interactive physical kinetic prototype and its digital simulation for architects using a series of proposed methods. Conventional architectural CAD applications alone are not always sufficient for illustrating ideas for adaptable and responsive architecture that can conditionally change its states over time. The use of technologies from game design and robotics has a potential to extend the role of architects beyond merely providing static formal design solutions to various spatial problems. The paper introduces methods for rapid prototyping and real-time interaction between physical kinetic prototypes and a digital application environment for simulation using readily available commodity hardware, such as Arduino microcontrollers, 9g servo motors, Kinect sensors, and Unity 3D game engine software with its computational physics. The paper also presents case studies using the approach and discusses possible applications and assessment of this approach.

Keywords: Interactive prototypes, simulation, game engine, robotics.
Shape studies
Re-inventing ceramic tiles
Using shape grammars as a generative method and the impact on design methodology

Deborah Benrós¹, Sara Eloy², José Pinto Duarte³

¹ University College London
d.benros.09@ucl.ac.uk

² Lisbon University Institute
sara.eloy@iscte-iul.pt

³ University of Lisbon
jduarte@fa.ulisboa.pt

Abstract. The following paper describes the process and results achieved with the workshop entitled ‘Re-inventing Portuguese ceramic tiles’ reflecting on design methodology and design teaching. Workshop participants were invited to rethink ceramic tile patterns developing a different process which used shape grammars as a generative system. Each participant group developed a three stage task using shape grammars principles and methodology.

The preliminary results the work developed are of particular relevance in shape grammar research: firstly shape grammar formulae does not constitute an intuitive process to most creative designers which are often trained to design singular solutions for a specific problem, secondly more than one operative shape grammar can be formulated to represent the same corpus of solutions and lastly the generative potential of grammars transcends the normal capacities of the original grammarist aiding in design exploration and enlarging the corpus of feasible solutions.

This paper also reflects on the impact of shape grammars as a design methodology.

Keywords: Shape grammar, patterns, ceramic tiles, 2d, 3d

1 Introduction

Previous studies on shape grammars in teaching focused on how these can be used as an effective design methodology. In several academic institutions shape grammars are part of the curriculum and are being taught to young designers. As examples Massachusetts Institute of Technology, University of Lisbon, University College London and others. Most of these programs offer either undergraduate or post
graduate modules where grammars are taught using a practical approach. In addition they have been showcased in workshops to test design processes and design languages [1]. Similarly to other ruled based systems they confer a level of systemization and structure required to efficient and consistent designs. They also allow for an efficient way of testing and exploring design solutions or simply providing diversity and maintaining consistency through mass customization processes whilst avoiding an important problem designers face - fixation.

This paper focuses on the results of the workshop ‘Re-inventing Portuguese ceramic tiles: Using shape grammars as generative method’. The workshop took place in Porto University School of Architecture in April 2013, counted with the contribution of 10 participants, most with no previous experience or exposure to shape grammar theory.

The aims were looking at Portuguese traditional ceramic tiles design techniques as a starting point to re-invent patterns and textures considering the use of different design. Ceramic tiles occupy a particularly important place in the overall panorama of Portuguese artistic creativity and have been use in Portugal since the 15th century without interruptions until today. In the 50’s ceramic tiles had a revival and several artists were called to produce artistic panels both to buildings and urban spaces (see example in Fig. 8). New design processes and manufacture techniques may be use nowadays to innovate in this well recognized Portuguese industries introducing new designs and exploring the possibilities of tridimensionality and the use of other materials.

The main goal was to use shape grammars as a design methodology for the creation of bi-dimensional ceramic tile patterns. Shape grammars were also used to analyze and describe the designs and produce new solutions. The workshop was carried out though the extent of a day, in a total of 8 hours and it was divided into 4 mains tasks:

1. Introduction to shape grammars, shape rule formulation and derivation process
2. Creation of a new shape grammar to generate ceramic tiles patterns
3. Rule extraction and shape grammar inference
4. Creation of shape rules to convert a bi-dimensional shape grammar to a three dimensional

The following paper will focus on the use of shape grammars as a design methodology and its benefits on design creation focusing tasks 1 to 3. It is organized into four sections. Respectively: precedents, methodology, results and conclusion with discussion on findings and future work.

2 Precedents

Shape grammars can be defined as a formulation composed by geometric shape rules or transformations that once applied recursively and ordered in successive steps can
produce a family of designs that share the same design principles, features or style [2].

It proved to be an efficient way to describe architectural styles, design and even painting styles.

The first experiment on an architectural example was the Palladian grammar [3]. The grammar reproduced bi-dimensional villas floor plans and was the first real implementation of the shape grammar theory into a design context. Another important precedent was the Kindergarten grammar [4]. This grammar encoded a set of limited shapes lexicon provided in the children board game - composed by building blocks. This work reflected on the different spatial relations between the blocks provided and in basic additive rules to describe compositions. This work inspired the methodology used to depict shape grammars and illustrate shapes.

Another significant work was the study developed using shape grammars as a way to describe Islamic ceramic patterns [5]. This study dwells on the wealth of patterns provided by Islamic geometric tiles and proposes a generative design methodology to recreate these (Fig. 1). This grammar does not attempt to replicate the designer role by replicating the design process originally used. Instead it attempts to recreate patterns by shape emergence. To do so, different Islamic patterns were studied as case study and its inherent shapes analyzed. Sixteen different shapes were identified as lexicon in different compositions. All of these polygonal present diverse shapes. Most of them are regular polygons based on bi-dimensional designs. Among these shapes one can identify stars, wedges, squares, pentagons, arrows, and hexagons. Jowers and Prats [5] came up with a methodology that could potentiate the range of designs desired. The different patterns were observed presenting a vertical, horizontal or a 45 degrees rotation orientation. The issue of symmetry is closely related to the question of repetition. Taking this into account Jowers and Prats [5] used the square tile shape as a starting point and selected only a half portion. This half portion was selected through the main tile diagonal which could be easily mirrored. The obtained shape is a square triangle with a vertical, a horizontal and a main diagonal border. These boundaries became the directors of the whole pattern design. The grid is then placed as an auxiliary method to the design. The grid lines are then traced parallel to the border of the tile triangle forming a diagrid. This diagrid is constituted of construction lines represented graphically with dotted lines. Labels are placed between dotted lines and mostly on its endpoints. These labels, in the shape of dots, helped identifying the endpoints. By filling between the dots a continuous line is generated allowing for changes of direction and configuration. This grammar showcases a similar formulation based on a grid.
It also shows a different type of grid, a non-orthogonal. It sums successfully the potential of shape grammar formulation and its generative power even when using a limited set of rules as ten which allows an unrestricted set of examples and a significant number of possible design solutions. This grammar was shown to the workshop participants as an example and reference.

3 Methodology

The workshop was targeted to both experienced and non-proficient grammar users. Shape grammars conferred an alternative method to describe and generate design to the participants as well as a way to transform the design process into a more efficient system. To the organizers the workshop provided a controlled environment where theories on shape grammar inference process could be tested using real designers and a mix of experienced and not experienced grammarians.

In this research the term ‘designer’ is used for the ones that design and ‘grammarians’ for the ones that research on shape grammars. A third group of ‘grammarians designers’ is used to refer to the designers that use shape grammar systems in their design projects and a fourth group, ‘traditional designers’, to refer to the designers that don’t use grammars at all.

In order to achieve the desired outcome and provide significant answers was important to provide a basic knowledge foundation regarding the basic shape grammar formalism, shape grammar graphical representation and the generation process commonly known as derivation. With this in mind an introduction and examples were provided. This constituted the first stage. The second stage encompassed an introductory task in order to familiarize participants with grammar methodology. Groups of 2 to 3 participants were formed and each team was asked to develop a brand new shape grammar. This shape grammar had to be graphically
represented through a set of shape rules. In addition they had to provide operable
design solutions developed using the grammar originally created.
For this first task some conditions were pre-set:

1. Each team had to generate a complete new shape grammar to create bi-
dimensional ceramic tiles patterns
2. A lexicon of shapes was provided, participants had to exclusively use these
shapes for the grammar formulation
3. The set of design rules had to be graphically illustrated
4. Design solutions as outcome of the shape grammar had to be provided

In order to facilitate the experience the lexicon of shapes was provided using three
dimensional solids. This proved to be a successful method of fully grasping shape
grammars procedures. Usual grammar classes often recur to sketching and paper
tracing. Experience shows that this often limits the notion of embedding and the full
spatial experience of a shape. The hand scale solids allowed a more tactile experience
with a more significant spatial allowance and a way to develop both patterns and
shape relations in a back and forth continuous way between physical tiles and
sketching.

The supplied lexicon of shapes combined as shown in the Fig. 2 and Fig. 3:
100x100mm yellow square, 100x100x140 mm yellow triangle, 100x50 mm yellow
rectangle, 100x25 mm yellow rectangle, 50x50 mm orange square, 50x50x70 mm
orange triangle, 100x50 mm orange rectangle, 100x25 mm orange rectangle. The
shapes were provided as MDF cut-outs of colored boards. Each team was provided
with a large number of samples, enough to illustrate rules and generate design
solutions.

Often these simple spatial relations could be captured by additive shape rules. To
each shape another was added or combined into a specific position to create a new
situation.

Most groups recorded those rules by simple sketches. A small group of participants
illustrated the rules using the shapes provided. Once these were identified and
selected, the teams combined the different groups of shapes to develop a pattern. In some of the grammars provided there were a clear distinction between shape rules to describe spatial relations and rules to generate a pattern or a tiling matrix.

Similarly to the work of Prats and Powers [5] on ceramic Islamic patterns, which served as a reference for the workshop, most rules were clearly segregated between design rules and tiling rules. There were however exceptions where patterns and tilling patterns were coincident. No difficulties were encountered by the participants with the grammar formulae or standard representation.

The results of this experiment were diverse in theme and in outcome. Different groups opted either by bi-dimensional planar patterns or by exploring three dimensionality of the solids provided playing with voids, rotations and different solid thicknesses.

Shape grammar clearly assisted as creativity aider, helping the designers to generate rich and diverse solutions. Amongst the different groups diverse solutions and grammars were originated despite the initial limitations and the pre-set lexicon. The provision of shape rules did not inhibited design and the creators did not feel limited by the restrictions imposed. Shape grammar as a design methodology for tile patterns proved successful.

Illustrated below is the work of team A (Fig. 4 and Fig. 6) and team B (Fig. 5 and Fig. 7). These two teams are presented here as a sample of the work generated in the course of the workshop. They are representative of the variety of shape rules and patterns created given a fixed number and range of shapes as lexicon. The approaches followed are quite distinct although the starting point was similar. Both teams starting by experimenting different spatial relationships with the shapes provided. Team A was interested in providing linear bands that framed the composition vertically whilst team B was interested in the concept of void versus volume.

Team A shape grammar can be recreated using an addition strategy where squares and rectangles are juxtaposed to form bands. The pattern can be developed using mostly addition rules. This is replicated in the derivation diagram in
Fig. 6. where clearly 70% of the derivation consists of addition. Furthermore the shape rules provided that consist the grammar are in its majority addition rules followed by subdivision rules. Fig. 4 illustrates the real design solution generated in the workshop and later described in Fig. 6. Team B’s pattern is pictured in

Fig. 5. This pattern explores the notion of square repetition that is commonly used in ceramic tiles. Even though the basic square repetition is present the pattern and its grammar allow for great diversity and the omission of repetition. Team B showcased a very different strategy where both addition and subdivision rules occupy a place of relevance in the grammar. Deletion rules were also implemented to originate voids in the pattern. Both teams and their patterns allow a great level of liberty and potentiate the omission of repetition whilst playing with a limited corpus of shapes. This experiment proved the creative potential of shape grammars when applied to bi-dimensional patterns and with the same vocabulary of shapes.

The second task consisted on the replication of a common task developed by grammarians, the rule inference. Traditionally shape grammars are efficient methods of describing design languages and design families. The first design application of shape grammars was the recreation of Palladian villas [3]. This work aimed at identifying the key design principles of the extensive body of work of ‘domestic’ Palladian architecture, inferred design rules and created a shape grammar. This shape grammar was a powerful tool that encoded expert knowledge retained in the geometries, proportions and spatial relations originally used. It also allowed the recreation of the original corpus of designs and the generation of a new corpus that followed the principles of the family of solutions. Not much has been discussed about the inference process even though many authors used it in the past to recreate Prairie [7] and Malagueira houses [8], Wren city churches [9], Taiwanese houses [10], to name a few.
Re-inventing ceramic tiles - Using shape grammars as a generative method and the impact on design methodology

Fig. 6. Team A shape grammar and derivation
Nevertheless the inference process is an intensive and intuitive trial error process. The automation of the inference has been attempted and tested in works such as the city modelling project [6] and in the car design industry [11].

The second task had an undisclosed goal, to test the inference process put into place by different participants. It allowed testing how different participants would infer shape rules given a same design example. Each participant team was provided images containing ceramic tiles’ patterns. Each group was invited to analyze the
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pattern and generate a grammar that would efficiently replicate the family of patterns as illustrated in the picture (Fig. 8). The same image was provided to two of the participant teams for comparison purposes. Fig. 8 shows one of the patterns provided, and a diagram with the dissected pattern. Intentionally this was the pattern that was tested simultaneously by the two teams.

![Image](image1.png)

**Fig. 8.** (left) Ceramic tiles pattern as provided to Team A and B (Portuguese artist Maria Keil)

**Fig. 9.** (right) One of the teams inferring shape rules and its graphical representation.

Generally in literature to each grammar is attached a specific language. Moreover most grammars were developed to describe a specific style. Once this has been achieved grammarians will focus in other languages. To the extent of our knowledge no substitute grammar has been published with the aim of proposing a valid alternative to a grammar specifically created to replicate languages with the exception of previous work on the Alternative Palladian grammar [12]. This task was important to test how different grammarian designers would propose rules to describe the same body of work.

Using the first task as a reference most groups started by identifying the lexicon used in the images provided. This informal task was not formally suggested but was consistently used by all groups as a way to subdivide the problem into manageable items.

**Fig. 9.** The teams were encouraged to disregard the tiling matrix and its basic square shape and focus on the pattern geometry. Team A identified all shapes/colors recurrent in the pattern. At a second stage the different combinations and spatial relations between shapes were studied and simply sketched. From the various possibilities team A selected the feasible rules hypothesis and ruled out redundant rules. Additional rules were also created to combine in big scale square matrix different spatial relations.

Simple derivation sketches were carried out to test the grammar and recreate the original pattern as shown in Fig. 8. The grammar created can be classified according to Knight as unrestrictive type of grammar since also allows an array of solutions that follow the design rules created but do not necessarily relate with the original solution requiring a level of intelligent use to generate the original design [13]. It also proposes an extensive group of shape rules, as shown in the diagram above (Fig. 10).
Team B followed a similar initial methodology. Also focused on the different shapes and spatial relations to ultimately attempt to rationalize all the examples encountered/identified. To the extensive list of shapes colors and spatial relations identified, they identified a standard basic shape. The team observed that most of the geometries encountered could be described by a diagonally split square colored by contrasting dark/light colors. The split square and its division line were then easily represented by square with an inner dot label. The position of the label near one of the vertexes described the tone contrast and direction of split. From this point simple transformation rules were replicated were to a basic shape another one was added with a specific rotation or circumstance as allowed by the pattern. This grammar proved to be elegant, compact and descriptive. It allowed the design of the original corpus and other solutions easily identified as family related solutions (as shown in Fig. 11).

Fig. 10. Team A inferred shape grammar

Fig. 11. Team B inferred shape grammar

Fig. 12. Design created by the grammar of both Team A and B

Team A showed a deep concern by the shapes and patterns to be illustrated and had more difficulties exploring the shape grammar methodology resulting into a more extensive set of rules. Team B embraced shape grammars formulae and experimented with labels which resulted into a more elegant concise grammar. Nevertheless, both grammars proposed by team A and B are feasible and respond to the problem
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formulated as shown in Fig. 12 illustrating the pattern that originated the grammar and a new one that was produced with the same grammar.

4 Results

The results achieved by team A and team B unraveled important issues that contribute to the overall knowledge about shape grammars and generative methods in designs:

1. Shape grammar methodology allows for more than one grammar to describe the same body of results or languages. Different grammars may generate the same corpus of design but also have the potential to generate different solutions.
2. Restrictive and descriptive grammars allow for a level of precision useful to replicate an existing body of work.
3. Unrestrictive grammars allow for useful design exploration by setting specific design principles but not over restricting outcomes.
4. Descriptive shape grammars result into an extensive set of rules.
5. The use of labels can aid in the optimization of grammars and result in an elegant, concise and intelligent grammar.
6. More than one grammar can be feasible responding to the problem formulated.

Results also showed that the use of shape grammars both for creating traditional and new patterns of ceramic tiles is a feasible and useful design strategy that, with the use of digital tools to enhance mass customization, enable the creation of alternative design, exploring the graphic richness of this type of artistic work.

5 Conclusion

Shape grammars provide an efficient methodology for design. This has been arguably one of the biggest controversies between traditional designers and grammarians and grammarian designers. Traditional designers overlook shape grammars as an easy method to allow plagiarism or ‘pastiche’ design and fail to see the real benefit of the implementation of grammars in design methodology, design teaching and practice.

The workshop organized and discussed had two major goals, to test the application of shape grammars in design methodology and to analyze how the inference process of grammar rules can be described and processed efficiently.

For the workshop participants the grammar methodology was clearly a useful method that could be further applied in design. Grammars provide undoubtedly a good alternative as design process potentiating creativity and the exploration of feasible design solutions. As a rule based system it is a successful method to allow for the creation of diverse corpus of solutions.

For the workshop organizers it allowed to test the theory that more than one grammar can be employed to describe the same body of work. It also proved that
shape grammars do not require a deep and extensive know-how to be employed and can, contrary to some sources, be easily taught and applied.

The previous sections described two main tasks developed during the workshop ‘Re-inventing Portuguese ceramic tiles: Using shape grammars as generative method’: the development of a new design grammar and the inference of a grammar from a given example. The first task aimed at proving the efficiency of grammars as design method for both teaching and in practice. The second task tested and analyzed the inference process. Both tasks proved useful as learning tools for the proficient use of grammars.

The first task was based on a limited set of predefined variables, the lexicon. Despite the limitations the participants were able to generate 5 distinct grammars all using the same limited set of shapes as lexicon. From these grammars a significant number of shape rules were developed generating different solutions. The experience lasted 2 hours, used inexperienced participants and outcome showcased diversity and design creativity. The results prove the potential of shape grammars as design tools.

The second task tested the rule extraction process. This task helped prove that two distinct grammars can replicate the same design corpus whilst allowing an additional corpus of different design solutions. It also showed that restrictive grammars are useful in describing particular design languages but might restrict the production of novel designs. Whilst unrestrictive grammars might fail in precision but potentiate design exploration.

These findings consubstantiate the usefulness of the grammar methodology.

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References

Design patterns from empirical studies in Computer-Aided Design

Rongrong Yu ¹ and John Gero ²

¹ The University of Newcastle
rongrong.yu@uon.edu.au

² George Mason University and University of North Carolina at Charlotte
john@johnero.com

Abstract. This paper presents the results from studying the effect of the use of computational tools on designers' behavior in terms of using design patterns in the conceptual development stage of designing. The results are based on a protocol study in which architectural designers were asked to complete two architectural design tasks with similar complexity, one in a parametric design environment and one in a geometric modeling environment. To explore the development of design patterns during the design process, the technique of 2nd order Markov model was used. The results suggest that there more design patterns were adopted in the parametric design environment than in the geometric modeling environment. Also, there are more design patterns related to structure in the parametric design environment than in the geometric modeling environment.

Keywords: Design pattern, Markov model, protocol studies.
Shape Grammars for architectural design
The need for reframing

Pieter Pauwels¹, Tiemen Strobbe¹, Sara Eloy² and Ronald De Meyer¹

¹Ghent University
{pipauwel.pauwels, tiemen.strobbe, ronald.demeyer}@ugent.be;

²Lisbon University Institute
sara.eloy@iscte.pt

Abstract. Although many shape grammars and corresponding implementations have been proposed, shape grammars are not widely adopted by architectural designers. In this paper, we therefore look for the barriers of implementing and using shape grammars for architectural design. We do this by outlining several implementation strategies of shape grammars, we briefly point to our own graph-based design grammar system, and we analyse the resulting overview using theories on how designers think and act upon incoming information. Based on this analysis, we develop and suggest how design grammars might best be implemented and used for architectural design relying on the information technologies available at this particular moment of time.

Keywords: architectural design, design space exploration, design thinking, shape grammar.
From idea to shape, from algorithm to design
A framework for the generation of contemporary façades

Inês Caetano\textsuperscript{1}, Luís Santos\textsuperscript{2} and António Leitão\textsuperscript{1}

\textsuperscript{1}University of Lisbon
\{ines.caetano, antonio.menezes.leitao\} @ist.utl.pt

\textsuperscript{2}University of California Berkeley
luis_sds82@berkeley.edu

Abstract. Nowadays, there is a growing interest in buildings' envelopes presenting complex geometries and patterns. This interest is related with the use of new design tools, such as Generative Design, which promotes a greater design exploration. In this paper we discuss and illustrate a structured and systematic computational framework for the generation of facade designs. This framework includes (1) a classification of facades into different categories that we consider computationally relevant, and (2) an identification and implementation of a set of algorithms and strategies that address the needs of the different designs.

Keywords: generative design, facades, algorithms.
Pattern, cognition and spatial information processing

Representations of the spatial layout of architectural design with spatial-semantic analytics

Kai Liao\(^1\), Bauke de Vries\(^1\), Jun Kong\(^2\) and Kang Zhang\(^3\)

\(^1\)Eindhoven University of Technology
{kliao, b.d.vries}@tue.nl

\(^2\)North Dakota State University
jun.kong@ndsu.edu

\(^3\)University of Texas at Dallas
kzhang@utdallas.edu

Abstract. In this paper, we review and extend the idea of Alexander’s “pattern language”, especially from the viewpoints of complexity theories, information systems, and human-computer interaction, to explore spatial cognition-based design representations for “intelligent and adaptive/interactive environment” in architecture and urban planning. We propose a theoretic framework of design patterns “with spatial information processing”, and attempt to incorporate state-of-the-art computational methods of information visualization/visual analytics into the conventional CAAD approaches. Focused on the spatial-semantic analytics, together with abstract syntactic pattern representation, by using “spatial-semantic aware” graph grammar formalization, i.e., Spatial Graph Grammars (SGG), the relevant models, algorithms and tool are proposed. We testify our theoretic framework and computational tool VEGGIE (a Visual Environment of Graph Grammar Induction Engineering) by using actual architectural design works (spatial layout exemplars of a small office building and the three house projects by Frank Lloyd Wright) as study cases, so as to demonstrate our proposed approach for practical applications. The results are discussed and further research is suggested.

Keywords: Pattern language, complex adaptive systems, spatial cognition, design representations, spatial information processing, Artificial Intelligence, visual language, Spatial Graph Grammars (SGG), spatial-semantic analytics.
The geometry of Chuck Hoberman as the basis for the development of dynamic experimental structures

Márcia Anaf and Ana Lúcia Nogueira de Camargo Harris

Abstract. The cognitive-theoretical foundation referring to teach drawing as a way of thinking, as well as the construction of the environment by means of drawing using transforming geometries and the formal and para-formal computational process, creating unusual geometries through generative design processes and methodologies, can be seen as some of the main possibilities in exploring dynamic experimental structures for an Adaptive Architecture. This article presents the development of a model for articulated facades, inspired by Hoberman’s Tessellates, and his Adaptive Building Initiative (ABI) project to develop facades models that respond in real time to environmental changes. In addition, we describe an experiment based on the retractable structures, inspired by Hoberman’s work and experimentations. Solutions for responsive facades can offer more flexible architectural solutions providing better use of natural light and contributing to saving energy. Using Rhinoceros and the Grasshopper for modeling and test the responsiveness, the parametric model was created to simulate geometric panels of hexagonal grids that would open and close in reaction to translational motion effects, regulating the amount of light that reaches the building.

Keywords: Parametric architecture, Hoberman’s Tessellates, Adaptive Building Initiative (ABI), Articulated Facades, Complex Geometries, Retractable structures, Retractable polyhedra.
Material computability of indeterminate plaster behavior

Aslı Aydın¹ and Mine Özkar²

¹ İstanbul Bilgi University
asliaydin87@gmail.com

² İstanbul Technical University
ozkar@itu.edu.tr

Abstract. In this study, we revisit the concepts of abstraction and materialization with regards to the theoretical framework of new materialism. Underlining the changing relationship between design through abstraction (DtA) and design through materialization (DtM) in design history, we propose an integration of the two towards achieving design emergence. Additional to a theoretical framework, we provide a showcase through material experiments of plaster and abstractions in the form of shape computation. We discuss results as parameters for future digital implementations and potentials for design practice and education.

Keywords: Shape computation, new materialism.
A design tool for generic multipurpose chair design

Sara Garcia and Luís Romão
University of Lisbon
{sgarcia,lromao}@fa.ulisboa.pt

Abstract. Product classes share the same basic abstract layout, despite their great diversity. The present paper intends to (de)code the variety of types embedded in the class of multipurpose chairs. The contribution of this research is the development of a generative design tool, to be used at the conceptual chair design stage. A framework of five stages is proposed: (1) sample definition, considering chairs with a large diversity of types; (2) analysis of the syntax and semantics of the class through ontological classification; (3) development of a generic shape grammar, innovatively applied to product design; (4) implementation of a digital tool, that provides an interface to manipulate the chair components visualized in a 3D digital model; and (5) user evaluation of the program, in order to draw conclusions on the usability and usefulness of the tool and to collect inputs for further developments.

Keywords: Multipurpose chairs, ontology, generic shape grammars, generative design tool, user experience.