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open systems 2013

Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia

National University of Singapore

Edited by: R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer

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OPEN SYSTEMS
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Department of Architecture
School of Design and Environment
National University of Singapore

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OPEN SYSTEMS – THEME

Contemporary challenges require inclusively integrated approaches to designing. Constrained by established modes of practice, such integration is impossible without a radical commitment to openness. In response to this need, the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013) brought together contributions that engage with open systems in all aspects of architectural and urban design: open with respect to the scale of the design objectives and the context, from a building component within a building system to a neighbourhood or city within its urban and rural context; open with respect to the domains being considered, from planning to sustainable performance of a building or city; open with respect to the collaboration of disciplines and participants, from ad-hoc brainstorming to a rigorous process of consultation and feedback; open with respect to design methods and techniques, from physical modelling to digital prototyping; open with respect to design models and representations being adopted, from a parametric exploration to an ontological delineation considering Building Information Modelling, Built Environment Modelling or City Information Modelling; open with respect to the tools and applications being adopted, despite interoperability issues, from modelling to simulation and assessment; open with respect to the learning approach being adopted, from informal interaction and sharing to formal design education; open with respect to the open source approach being adopted in research and development, in order to gather community involvement and use. The conference was held 15-18 May 2013 at the Department of Architecture, School of Design and Environment, at National University of Singapore.

By focusing on the theme of Open Systems, CAADRIA 2013 aimed to explore all these aspects and more, and raise awareness to the need of breaching disciplinary boundaries and reaching creative communities at all levels of expertise, by pooling resources, knowledge and practices, and integrating them through the adoption of open systems.

Rudi Stouffs, Patrick Janssen, Stanislav Roudavski, Bige Tunçer

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FOREWORD

The annual CAADRIA (Association for Computer-Aided Architectural Design Research in Asia) conference provides an international community of researchers and practitioners with a venue to exchange, to discuss and to publish their latest ideas and accomplishments. This volume contains the 91 research papers and 8 practice work presentations that were accepted for presentation at the 18th International CAADRIA Conference, hosted and organised by the Department of Architecture, School of Design and Environment, at National University of Singapore. The contained papers can be obtained digitally from CUMINCAD (http://cumincad.scix.net) via individual or institutional subscription to CAADRIA (http:// www.caadria.org).

This volume is the outcome of an extensive collaborative effort of a team of volunteers, and it marks another year of growing quality and strength in the history of CAADRIA. Calls for papers in June of 2012 resulted in the submission of a record number of 259 abstracts. These were initially reviewed by the paper selection committee, which invited 209 abstracts for further development. Of these, 130 full papers were submitted to the full paper review stage. Fortunately, we could count on 79 international reviewers to assist us in the full review stage. Minimally two, though often three, international reviewers carried out a double-blind review of each submitted paper. Following the reviewers' recommendations, 91 papers were finally accepted for publication. In addition, we invited presentations of practice work for a special conference session on Open Systems in Practice, resulting in 17 submissions. These were reviewed by the paper selection committee and, finally, 8 were accepted for publication.

We congratulate the authors for their accomplishment. Next to the authors, the reviewers, who volunteered valuable time and effort, deserve our sincere thanks and acknowledgements. We sincerely thank the organising team at National University of Singapore, in particular Dr. Beng Kiang Tan, conference chair. We remember the late Dr. Milton Tan, one of the founding members of CAADRIA and conference chair of the 5th International CAADRIA Conference, in 2000, also hosted and organised by the Department of Architecture, School of Design and Environment, at National University of Singapore.

On the following pages, we acknowledge and thank those who contributed to the production of this volume. In closing, we sincerely thank the CAADRIA community for offering us the honour to serve as members of the paper selection committee for CAADRIA 2013.

Rudi Stouffs, Patrick Janssen, Stanislav Roudavski, Bige Tunçer

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Evolution of Interoperability in Architectural CAD and BIM
Charles M. EASTMAN

Architectural Engineering at Gardens by the Bay
Adrian LAI

Engineering Architecture at Gardens by the Bay
Yacine BOUZIDA

A Practical Method of Computational Design and BIM in Nikken Sekkei
Tomohiko YAMANASHI

Evolution of Interoperability in Architectural CAD and BIM

Charles M. EASTMAN
Georgia Institute of Technology, Atlanta, GA, United States

Short Biography. Charles Eastman is Professor at the College of Architecture and the College of Computing (joint appointment) and Director of the Digital Building Lab, at Georgia Institute of Technology, USA. He is a pioneer of AEC CAD, developing research in 3D and early solid and parametric modeling systems for the building industry starting in the middle 1970s. He was a faculty member at Carnegie Mellon University (CMU) where he started the Architecture PhD. Program and founded ACADIA (Association for Computer Aided Design in Architecture) in 1982. At CMU he directed several laboratories, including the Center for Building Sciences and CAD-Graphics Lab. He also taught at UCLA where he served as the Director of the Center for Design and Computation before his current position at Georgia Tech. At Georgia Tech he directs the Digital Building Laboratory that is sponsored by twelve AEC companies and undertakes collaborative research with them. In addition, he currently has projects with the Precast Concrete Institute and the Charles Pankow Foundation, with the America Institute of Steel Construction and the American Concrete Institute, defining BIM exchange standards for these industry areas. He recently completed work with the National Institute of Standards and Technology on improving IFC semantic foundations and has other projects in advanced BIM.

In 2001, he was conferred the Award of Excellence in Research by ACADIA for his achievements and contributions to the field of computer aided design in architecture. In November 2006, he was awarded the BIM 2006 BuildingSMART Open Data Award by the International Alliance for Interoperability. He is co-author, with Paul Teicholz, Rafael Sacks and Kathleen Liston, of the Building Information Modeling Handbook, that came out in a second edition in March of 2011 from John Wiley and Sons. Earlier, they wrote Building Product Models for CRC Press. He is author of over 100 papers on BIM, parametric modeling and on databases and product models. He also authored books in the areas of CAD, engineering and geometric modeling.

Abstract. Since the beginning of CAD, the need to share data between applications has been an issue. The concept of a neutral file arose in the 1970s has evolved into current ideas about product models and BIM servers. This evolution continues because limitations exist for all of us in supporting different collaborative flows. Major undertakings are being made to address interoperability. This talk will address both the history, the evolving interpretation of need, and where interoperability is going currently and expected to go in the future.

Architectural Engineering at Gardens by the Bay

Adrian LAI
Meta Studio and Wilkinson Eyre Architects, Singapore

Short Biography. Adrian Lai graduated from the Architectural Association (AA) and remained in London to work on a variety of UK and international projects with Wilkinson Eyre Architects and David Walker Architects. He completed the 438m-tall Guangzhou International Finance Centre in China and One Coleman Street commercial building in Central London prior to returning to Singapore in 2008 with Wilkinson Eyre Architects to deliver the international competition-winning Gardens by the Bay. Part of the Wilkinson Eyre Architects team in London since schematic design stage, Adrian Lai returned to Singapore in 2008 to oversee the construction and implementation of Wilkinson Eyre's architectural design of the two climate-controlled biomes and the habitable – and at 50 metres, the tallest – Supertree in Singapore's new $1 billion city centre Gardens by the Bay South.

Adrian Lai has been practising for ten years and is a registered Architect in the United Kingdom. He has spent most of his waking hours designing geometrically complex facades, integrating highly demanding requirements into coherent built environments and delivering challenging briefs as materialised ideas. He teaches a Design Studio at the National University of Singapore Department of Architecture while continuing in his role as Wilkinson Eyre's Country Representative in Singapore.

In June 2012, he launched META as a platform for the dissemination of ideas for materiality and atmospheres; and their intertwining in our built environment. META is a design practice helmed by Adrian Lai and based in Singapore. META finds opportunities in projects of all scales and typologies.

Abstract. See the abstract under Yacine BOUZIDA.

Engineering Architecture at Gardens by the Bay

Yacine BOUZIDA
Passage Projects, Singapore

Short Biography. Yacine Bouzida is a French Architect and Structural Engineer. He graduated from Ecole des Ponts et Chaussées in Paris, an engineering institution which exists for almost 400 years. He worked in France and the UK on several high profile projects like stadiums, airports and museums specialising in light-weight and complex geometry structures. In the UK he joined Atelier One where he was in charge of the structural design of the two conservatories at Gardens by the Bay.

After working for Atelier One on Gardens by the Bay as a site engineer, he started Passage Projects a consultancy firm based in Singapore to promote creative structural engineering and multi-disciplinary approach in the construction industry.

Yacine is a lecturer at Ecole des Ponts Paris-Tech and also at Ecole d'Architecture des Beaux-arts in Paris where he was extensively involved in promoting multidisciplinary between architects and Engineers by organizing workshops and studios.

Abstract. The recently completed Gardens by the Bay presented different challenges at different stages of its conception, production and delivery. One constant from the very early phases of its design to its development for structural resolution, fabrication and ins tallation is the geometrical evolution and resolution of the two glazed Conservatories and the multi-layered Supertrees. This talk focuses on the two Conservatories enclosing the cool – dry and cool – moist environments. Wilkinson Eyre Architects and Atelier One will recollect on behalf of the rest of the Design Team to reveal how the technical, pragmatic and aesthetic were resolved between Architect and Engineers in an iterative feedback loop to meet the common ambitions of each discipline and ultimately, the Client – the Government of Singapore's National Parks Board and Gardens by the Bay.

A Practical Method of Computational Design and BIM in Nikken Sekkei

Tomohiko YAMANASHI
Nikken Sekkei, Tokyo, Japan

Short Biography. Tomohiko Yamanashi is the Principal Executive Officer at Nikken Sekkei, Japan. He graduated from the Tokyo National University of Fine Arts and Music and completed his Master Course of Urban Engineering at the University of Tokyo. He joined Nikken Sekkei in 1986 and is currently the Principal Executive Officer and also heads the BIM initiative. His work ranges from offices to museums and has won many prizes, among others, the 2011 Grand Prix of The Japan Institute of Architects for the Hoki Museum. He has also published papers on Architectural BIM.

Abstract. Nikken Sekkei has explored how we can innovate the quality of the architectural design method and the quality of design itself by introducing computers for the last ten years through the on-the-job basis. The method is called “computational design” and “computer-aided simulation” now, and the platform for it has come to be known as BIM. I would like to introduce our practical technique of the computational designs, application of the computer-aided simulations and integration by BIM through our practical projects, such as Sony City Osaki.

ABOUT CAADRIA

The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) promotes teaching and research in CAAD in Asia, and has members on six continents.

It was founded in 1996 with the following objectives:

- To facilitate the dissemination of information about CAAD among Asian schools of architecture, planning, engineering, and building sciences.
- To encourage the exchange of staff, students, experience, courseware, and software among schools.
- To identify research and develop needs in CAAD education and to initiate collaboration to satisfy them.
- To promote research and teaching in CAAD that enhances creativity rather than production.

CAADRIA organizes an annual conference, the first of which was held in 1996 in Hong Kong. Since then, 17 conferences have been held in Australia, China, Hong Kong, India, Japan, Korea, Malaysia, Singapore, Taiwan, and Thailand. The conferences provide an opportunity for teachers, students, researchers, and practitioners to meet each other and learn about the latest research in the field. The proceedings of the conferences are available both on line and in research libraries around the world.

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BUILDING INFORMATION MODELLING

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VISUAL ARCHITECTURAL TOPOLOGY

An ontology-based visual language tool in an architectural case library

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Abstract. This paper aims to develop a tool entitled "Visual Architectural Topology (VAT)" for encoding topological information within a case library. VAT can annotate design objects and their topological information within the unstructured information of a design case. By applying an ontology-based topological validation mechanism, VAT aims to establish a visual language for representing the "topological knowledge" of architectural design objects in a case library. The purpose of VAT is to extend the knowledge representation ability of a design case library, and to provide a foundation for development of a design-assistance tool performing the conversion and processing among semantic and geometric design information.

Keywords. Case-based design; case library; architectural topology; semantic ontology; visual language.

1. Introduction

Building information modeling (BIM) has been implemented by many commercial CAAD tools, and has been widely adopted in architecture, engineering, and construction practice. BIM was originally developed via research on building product modeling (BPM) (Eastman, 1999). BPM is composed of three types of information: semantic, topological, and geometric information concerning building components. Topology is the mathematical connections among building components, and is the fundamental aspects of parametric design (Eastman et al., 2008). Unfortunately, most BIM implementations lack necessary topological information for architectural design, such as spatial topology (Lobos and Donath, 2010). This shortcoming therefore impedes applications of BIM in the early conceptual design stage.

From the perspective of an information-driven approach, architectural design employing BIM can be regarded as the interconversion and processing of three types of design information. Experienced architects have meta-knowledge concerning conversion among the three types of design information. But novice designer must study past design cases, and try to reconstruct the conversion process. Design case libraries were originally assumed to play the role of knowledge depositories in the learning process. But case libraries are usually implemented employing database technology, which only extracts semantic information of case features as an index mechanism. Therefore most clues about conversion process among three types of design information are lost.

This paper is a follow-up study to the two previous projects "STR: Spatial Topology Retrieval" (Lin and Chiu, 2010) and "SSO: Smart Spatial Ontology" (Lin, 2013). This paper aims to develop a visual tool entitled "Visual Architectural Topology" (VAT) for the purpose of encoding architectural topologies within design cases of a house case library termed "OCS: Open Case Study" (Lin and Chiu, 2009). By applying previous research results, VAT aims to establish a visual language for representing the topological information of architectural design objects, and also to extend the knowledge representation ability of our design case library.

2. The Approach of Visual Architectural Topology

Knowledge representation in design cases is a major bottleneck in case-based design (CBD) and case-based reasoning (CBR) research (Heylighen and Neuckermans, 2001). Since design knowledge is usually implicit, especially in the case of ill-defined or unstructured information such as drawings, graphics and pictures, it is difficult to formalize this knowledge into a machine-processable format. As more BIM implementations are used in practical work, BIM may provide an "information-rich" depository of BIM-based case libraries in the future. However, for important precedents outside of practice or before the development of BIM, it is usually difficult to collect detailed information in order to construct BIM files. In contrast, unstructured information concerning design cases, such as the scanned design drawings and images, are nevertheless easily collected and stored in case libraries.

The current method for indexing unstructured information in design cases usually relies on the attachment of semantic tags. The advantages of this method are that it is open, flexible, and easy to implement. But simple semantic tags cannot adequately represent the topological information. Therefore, this paper proposes an open and adequately-formalized tool that can assist users to visually represent their interpretations of topological knowledge. Rather than providing a rigid

representation framework of architectural topology, the approach is based on (1) the semantic ontology of topology, (2) graphic annotations attached to unstructured information, and (3) visual validation when encoding topology.

2.1. SEMANTIC ONTOLOGY OF TOPOLOGY

An ontology is a "formal, explicit specification of a shared conceptualization" (Gruber, 1993), A knowledge chunk in an ontology can be represented by a triple set of "subject," "predicate," and "object" (Fensel, 2003). Development of an ontology therefore consists of the establishment of a formal language to describe design knowledge. As a topology represents correlations between design objects, the "predicate" represents the semantic or causal relationship among knowledge objects. For example, a spatial ontology has been proposed (Brennan et al., 2004) to represent three aspects of spatial knowledge: connectivity, proximity and orientation. However, most proposed ontologies can only represent what topologies are contained in a case, but cannot represent why and how a topology is composed in a certain way within the case, let alone allow users to state different interpretations or new types of topologies.

To assist users to associate semantic ontologies with spatial topologies, a visual tool named "smart spatial ontology" (SSO) was proposed in previous studies (Lin, 2013). SSO allows users to annotate semantic predicates on spatial topologies, and therefore provides a bridge between the semantic ontologies and spatial topologies of architectural spaces. However, the functions of SSO focused on spatial topology, and were restricted to the same declaration level of an ontology. For improving knowledge representation ability, VAT adds the cross-level function of declaring the predicates associated with different levels in a semantic ontology. For example, VAT can assign two "has" predicate with "ventilation" and "lighting" to a connective topology of "bedroom" and "atrium" in order to represent the design concept of the Azuma House. VAT therefore can not only associate topologies of design objects assigned by users with existed semantic features in a library, but also associate topologies with abstract concepts interpreted by users.

2.2. GRAPHIC ANNOTATIONS ON UNSTRUCTURED INFORMATION

Appropriate interfaces, which go beyond textual search and can deal with non-textual information, are therefore usually absent from case libraries. Since architects are educated to think and reason through visual information such as sketches and diagrams (Oh et al., 2004), graphic interfaces such as "SpaceScope" (Hwang and Choi, 2003) and sketch-based interfaces (Langenhan et al., 2011) have been proposed in order to improve retrieval in a case library. Visual approaches must rely

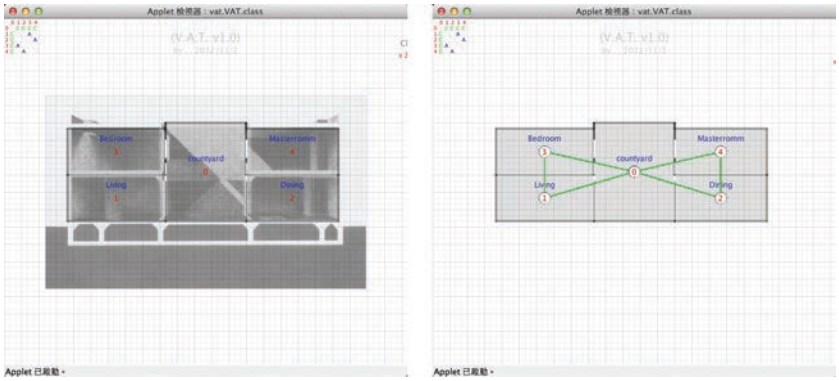

Figure 1. Graphic Annotations on the section drawing of the Azuma House.

on preceding mechanics, regardless of the topologies or ontologies of a case's contents. However, declaration of an ontology usually involves tedious expression of the semantic features of knowledge chunks. And while burdensome parametric inputs in BIM inevitably confuse architects, ontology-authoring tools such as Protégé perplex designers as well. Although visual alignment tools for ontologies have been proposed (Lanzenberger et al., 2008), alignment tools for semantic ontologies with visual knowledge resources are still absent.

In the previous studies, SSO therefore integrated graphic declarations with a search interface in order to deal with visual information in design cases. SSO can easily draw schematic spatial layouts while attaching graphic annotations for spatial topologies to the images of a house plan. VAT extends the graphic interface of SSO to the translation of more types of topologies than spatial topologies of plan drawings. For example, VAT can attach simple diagrams as graphic annotations to section drawings, site plan drawings, and interior and exterior photos, etc. For example, VAT can attach diagrams to a section drawing of Azuma House (Figure 1, left), and then the initial topologies of annotated object will be encoded (Figure 1, right).

2.3. VISUAL VALIDATION WHEN ENCODING TOPOLOGY

The knowledge-acquisition process usually employs a top-down approach and focuses on the validation and consistency of an ontology within a particular domain of knowledge. However, while this constraint may be adequate for most domains, it may not be able to satisfy the needs of the architectural design domain. Architects are typically educated to be creative, and are therefore encouraged to challenge pre-existing specifications of conceptualizations. Important precedents are therefore

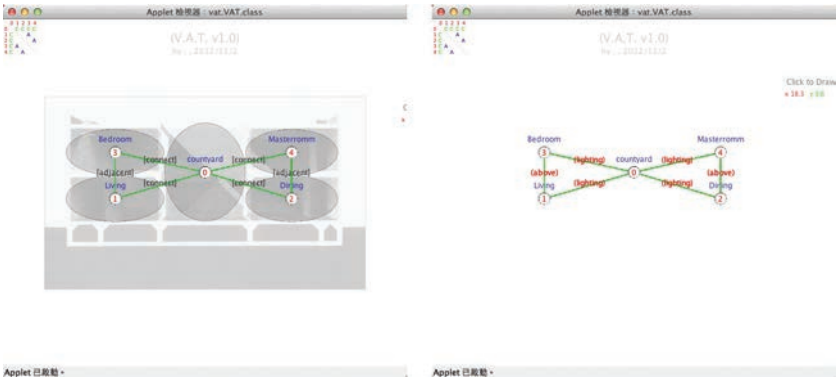

Figure 2. Interactive validation between encoded topology and semantic ontology in VAT.

collected on the basis of their unique concepts, but the more distinctive the concept of a design case, the smaller the valid domain of its design knowledge.

While a scholar has declared that "*designers reason from cases, not from principles*" (Boling, 2010), students are usually educated to transform or interpret cases, rather than to directly imitate precedents. Although most design information should be fixed and static within built precedents, designers' interpretations when analyzing built precedents may still vary with the times and technology. The valid domain of an ontology can therefore be restricted to the relevant information within a case, rather than a larger scope, such as building types. VAT can help user to interactively validate the encoded topologies by switching between schematic layouts of encoded topologies (Figure 2, left) and semantic ontologies (Figure 2, right). Based on the physically-oriented algorithm of STR, VAT will provide visual clues to help correcting conflicts by modifying geometric features within schematic layouts.

2.4. SUMMARY

Based on the prior knowledge consisting of the ontological techniques in SSO, and predefined topologies of STR, the VAT project is devoted to developing a visual language tool assisting users to represent the topological knowledge in design cases. VAT improves the topological knowledge representation of the OCS case library from the spatial topologies of house plans to free and open interpretations of other unstructured information in the library. Via the semantic association of ontologies with topologies, VAT can improve on SSO's graphic-based search mechanism, and assists users to retrieve and learn topological design knowledge more efficiently from unstructured information in design cases.

3. The Implementation and Primary Evaluation of VAT

The initial version of OCS consisted of a web-based application applying MySQL database software, and its access interface is implemented employing PHP and Flash. However, as a rational database management system, MySQL cannot easily be used to implement flexible metadata-authoring tools allowing users to develop different interpretations of case content. VAT therefore applies the MongoDB database software, which is a scalable, high-performance, open source, document-oriented NoSQL database management system (10gen, 2012). This system is used to store semantic ontology and graphic topological annotations within unstructured information. Since a "not only SQL" (NoSQL) database does not need a predefined schema of data tables, it is easier to represent open-structured design knowledge metadata and store flexible semantic ontologies. MongoDB is also a key-value store database, and there is no need for a fixed data model to store information. Through the use of MongoDB, VAT can thus easily store topological knowledge as objects, and can retrieve graphic annotations for unstructured information as documents from the library.

3.1. IMPLEMENTATION OF VAT INTERFACE

The initial version of SSO applied PROCESSING to implement an interactive interface for encoding spatial topology. PROCESSING is a simplified version of the Java program language, and offers a lightweight integrated development environment (IDE) in which visual design students can learn programing. In keeping with the emerging modern web-based interface technologies, VAT integrates the JavaScript based jQuery library and Processing.js, a JavaScript version of PROCESSING, to improve the compatibility of its interface with modern web browsers, which may not be compatible with Java plugins.

3.2. PRIMARY EVALUATION OF VAT

With the assistance of Web 2.0 technology, VAT aims to provide users a simple, efficient, and user-friendly means of representing, storing, indexing, and retrieving their acquired knowledge from unstructured information of design cases. However, the presentation of visual knowledge, such as topological knowledge contained in unstructured information, still faces challenges in both technological and user-experience aspects.

On the technological aspects, the prototype of VAT prototype can only attach 2D rectangle and ellipse shape object for now in order to simplify the validation algorithm of collision detection. This restriction can satisfy the interpretation of 2D

drawings, which are the primary goals of VAT. But obviously, it is difficult to interpret 3D topologies within perspective drawings or photos, which usually were the major reasons for why a user selects a case when our students tested VAT. Although some CG technologies, such as "Photo-Match" function of SketchUp, can covert 2D photos into 3D models. However, it still needs more investigations for how to simplify the manipulation for annotating 3D topologies as easy as 2D drawings.

On the user-experience aspects, the manipulation of VAT inherits the CAD-like operations of STR, which provides easier means to interpret geometric features of design objects, and should be familiar by users who have learned CAD software. However, CAD-like manipulation sometimes perplexes our students with too much geometric information and limited topological operations. Freehand-sketch interface obviously should be easier to record various graphic annotations attached by users. However, how to recognize topological information within freehand-sketches faces technological challenges and goes beyond the primary purpose of VAT.

Although the prototype VAT system is still rough and sometimes not intelligent enough with regard to user-experience aspects when testing by our students, VAT has some advantages over other approaches: (1) Semantic ontology can be attached to topologies, providing explanations facilitating learning and reasoning. (2) The integration of semantic ontology, graphic topology, and their visual sources of unstructured information allow the alignment of different abstract forms of design knowledge. (3) Simple diagrams can be added as graphic annotations to visually represent topological knowledge. (4) VAT adds predefined topologies to SSO as a validation mechanism assisting users to correct conflicts in knowledge representation.

4. Discussion

An architectural design information processing cycle was derived in our previous studies: (1) Declaration of the "semantic ontology" of design objects based on the building plan. (2) Translation of this semantic ontology into appropriate "topological relations" of design objects in response to the design context. (3) Interpretation of "topological relations" using the "geometric properties" of design objects to represent the chosen solutions. (4) Validation of the required "semantic ontology" based on the given "geometric properties." This information-driven approach motivates the following discussion.

4.1. TOPOLOGICAL KNOWLEDGE WITHIN DESIGN CASES

Topology is the representation of relations among design objects, and is therefore the key to parametric design in BIM. However, most BIM implementations

overlook topological information because of technical difficulties and the lack of consensus. From a mathematical point of view, the complexity of topological information increase linearly with the number of design objects when every topology involves only two objects. However, when a topology involves uncertain number of objects, such as “surrounding” relation, the complexity increase exponentially and the problem may even be insoluble. In addition, there seems to be no consensus in the academic and practical communities concerning what topologies should be integrated into a system. Unsurprisingly, most practical workers do not apply topology-based tools such as generating or automatic spatial layout software (Lobos and Donath, 2010). And even if BIM can be expanded with more topological information in the future, the implementation of BIM may only be able to represent what and how the topologies of design objects are, rather than why the topologies should be this way.

Architects obviously must apply different approaches to deal with topological knowledge. By extracting memories from past experiences or design cases, architects can employ abstracted patterns to reduce the complexity of topological problems. How architects can retrieve topological patterns, which usually are deduced from semantic information, in design problems, is the key to CBD and CBR. Since VAT has grafted semantic ontology with graphic topology, it should be very useful for designers who wish to retrieve, learn, and apply topological knowledge within design cases.

4.2. VISUAL REPRESENTATION OF TOPOLOGICAL KNOWLEDGE

Most of case libraries focus on the semantic features of design cases, but ignores the representation of knowledge within visual and graphic information in design cases because of technical difficulties in dealing with unstructured information. While a picture may be worth a thousand words, the original visual media within a design case may not be the best means representing topological knowledge.

Traditional methods of abstracting topological knowledge, such as topological matrices, graphs, bubble diagrams, and schematic layouts, can represent different degrees of abstraction for different purposes. However, as architects may deal with several different abstract levels of design information at one time, including mass sketches, schematic diagrams, and details of components, the one-time abstraction of topologies often cannot satisfy the needs of architects, and is not helpful to novices wishing to learn relevant knowledge. Since VAT can simultaneously represent topological information by matrices, graphs, and schematic layouts, and allows users to exclude unnecessary information from view, it should be easier for users to learn and use than systems presenting overly abstract mathematics or more primitive visual media.

4.3. INTERFACE FOR ENCODING AND RETRIEVAL

While one of the major purposes of developing a case library is to provide learning resources, some scholars claimed that important learning functions was absent from CBD systems proposed in previous studies, and noted that most such systems have no functions for acquiring and re-indexing design knowledge from cases (Heylighen and Neuckermans, 2001). To perform acquisition and re-indexing functions, it is necessary to have a user-friendly interface encouraging users to participate in acquisition actions, especially when acquiring unstructured information.

Regardless of whether textual tags or other visual approaches are employed, preprocessing is necessary to convert unstructured information into a machine-processable format. Since it is still difficult for machines to automatically recognize topologies within unstructured design case information, VAT provides a simple but intuitive interface assisting users in encoding and retrieving their perceptions. VAT can not only provide the results of analysis by users, which is performed through associations with semantic ontology, but also provide more clues about correlations among different cases in the library.

5. Conclusions

Since visual media can more easily represent architectural topologies, it is necessary to develop a visual tool in order to solve the problem of encoding, indexing, and retrieval of architectural topology meta-knowledge within a case library. This tool should provide necessary architectural topology functions, which can bridge the semantic and geometric information of design objects, and assist users in encoding and representing information conversion meta-knowledge among semantic, topological, and geometric forms of information.

The VAT project in this paper illustrates our methods of improving the representation of topological knowledge within the OCS case library. The recognition results of users applying VAT provide a visual language for communication between different agents in the system, including human designers and reasoning machines. VAT not only encompasses more topological knowledge within the design case library than spatial topologies in plan drawings, but also provides a foundation for development of the next generation of design assistance tools, which should be based on the conversion of the three types of design information used in BIM systems.

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References

10gen, I.: 2012, “MongoDB: Aglie and Scalabe”. Available from: <http://www.mongodb.org/> (accessed 2 November 2012).

Boling, E.: 2010, The Need for Design Cases: Disseminating Design Knowledge, *International Journal of Designs for Learning*, **1**(1), 1–8.

Brennan, J., Martin, E. A. and Kim, M.: 2004, Developing an ontology of spatial relations, *in* J. S. Gero, B. Tversky and T. Knight (eds.), *3rd International Conference on Visual and Spatial Reasoning in Design*, Key Centre of Design Computing and Cognition, Cambridge, MA, 163–182.

Dave, B., Schmitt, G., Faltings, B. and Smith, I.: 1994, Case-based design in Architecture, *in* J. S. Gero and F. Sudweeks (eds.), *Artificial Intelligence in Design ‘94*, 145–162.

Eastman, C., Teicholz, P., Sacks, R. and Liston, K.: 2008, *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, 2nd ed., John Wiley & Sons Inc, Hoboken, NJ.

Eastman, C. M.: 1999, *Building Product Models: Computer Environments, Supporting Design and Construction*, CRC Press, Boca Raton, Fla.

Fensel, D.: 2003, *Ontologies: A Silver Bullet for Knowledge Management and Electronic Commerce*, ed., Springer-Verlag, New York.

Gruber, T. R.: 1993, A translation approach to portable ontology specifications, *Knowledge Acquisition*, **5,** 199–200.

Heylighen, A. and Neuckermans, H.: 2001, A case base of Case-Based Design tools for architecture, *Computer-Aided Design*, **33**(14), 1111–1122.

Hwang, J.-E. and Choi, J.-W.: 2003, SpaceScope: Spatial Content-Based Retrieval of Architectural Floor Plans, *Digital Design – Research and Practice – Proceedings of the 10th International Conference on Computer Aided Architectural Design Futures*, Tainan, Taiwan, 53–62.

Langenhan, C., Weber, M., Petzold, F., Liwicki, M. and Dengel, A.: 2011, Sketch-based Methods for Researching Building Layouts through the Semantic Fingerprint of Architecture, *Proceedings of the CAADfutures 2011*, Liege, 85–102.

Lanzenberger, M., Sampson, J. J., Rester, M., Naudet, Y. and Latour, T.: 2008, Visual ontology alignment for knowledge sharing and reuse, *Journal of Knowledge Management*, **12**(6), 102–120.

Lin, C.-J.: 2013, Smart Spatial Ontology: Bridging Semantic Ontology to Spatial Topology, *Computer-Aided Design and Applications*, **10**(3), 489–497.

Lin, C.-J. and Chiu, M.-L.: 2009, Open Case Study, *CAADRIA 2009*, Yunlin, Taiwan, 393–399.

Lin, C.-J. and Chiu, M.-L.: 2010, Spatial topology retrieval: a visual approach for representing and retrieving spatial topology in a case library, *CAADRIA 2010*, Hong Kong, 147–154.

Lobos, D. and Donath, D.: 2010, The problem of space layout in architecture: A survey and reflections, *Arquitetura Revista*, **6**(2), 136–161.

Oh, Y., Do, E. and Gross, M.: 2004, Critiquing freehand sketching: A computational tool for design evaluation, *in* J. S. Gero, B. Tversky and T. Knight (eds.), *3rd International Conference on Visual and Spatial Reasoning in Design*, Cambridge, MA, 105–120.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 13–22. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

CUSTOM IFC MATERIAL EXTENSION

Extending IFC for parametric sustainable building design

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Abstract. The enormous variety of design systems and data formats utilised by the actors in the building design process has been recognised as a significant challenge for information exchange and project management. The introduction of the Industry Foundation Classes (IFC) data standard as a paradigm shift has opened a first time opportunity for smooth data and information exchange over the full range of design related parameters and processes, reaching beyond the classical constructional, economic and safety-related requirements. Moreover, IFC allows for the extension of the standard in further areas, corresponding to the specific design, project or client requirements. These user-driven extensions often close an important gap of the IFC standard and can subsequently be imbedded in new releases of the IFC data standard. This paper is focused on the extension of IFC for the purposes of controlling and managing material use, increasing material efficiency and closing material cycles over the life cycle of a building. Material efficiency is defined by the design scopes of material recyclability, element reusability and waste reduction. The practical implications of the data format extension and design-check performance are examined on the level of the data model and, subsequently, on the level of proprietary Building Information Modelling (BIM) software, based on a pre-defined case.

Keywords. Material efficient building design; IFC; parametric design; semantic design; BIM.

1. Introduction

The end of the year 2011 was marked by an event, expected, feared and widely discussed in the global media: the birth of the world's 7th billion inhabitant (Walsh, 2011) has become a reality in times when continuously increasing

resource scarcity and waste production are urgent global problems. Beyond energy resources, both the group of affected materials resources (i.e. metals, non-metals, a large group of organics), as well as the amount of hazardous and/or non-reusable compound waste (plastics, compound materials like glass-fibre concrete), are continuously growing – in contrast to the rapidly decreasing available landfill spaces. The building sector constitutes a significant proportion of this, consuming alone more than 50% of the material resources and producing more than 65% of the waste worldwide (Larsen et al., 2011). Causes for this can be identified in some of the specifics of the typical building design process: 1) environmental performance goals, such as material recovery and recyclability, material and element reusability and material waste reduction design, are not explicitly introduced as equally important as other design goals, 2) due to the highly divergent tools and data formats utilised in a typical building project, the necessary interdisciplinary sourcing data for environmental performance simulation is not available in unified quantity and quality, and hence, 3) no reliable design-stage simulation and optimisation of the building material efficiency performance over the entire life cycle is possible. This is a crucial point in the case of one-of-a-kind products like buildings which have a comparatively long life expectancy. In the context of aiming for a clean reintroduction of materials in possibly closed, low-waste material cycles it is essential.

With the introduction and progress of the IFC standard, a unified framework for the entire building related data generation, documentation and exchange was established. The IFC data format aims to offer semantic objects for all standard domains, actors, parameters, functions etc. of a building project. Moreover, it offers the toolkits for extending the data schemata to user-defined and project-specific design aspects. One weakness of the standard however is recognised in the complex workflows of both working with and especially extending the schemata for users without advanced software and programming skills. Nevertheless, there is currently no alternative open data exchange format that would allow the full semantic modelling of the complete set of multidisciplinary building related parameters and their interdependencies.

While IFC is the framework of the semantic content of all objects and the hierarchical organisation between them (geometrical, temporal, material etc.), BIM is the environment wherein these semantic objects exist in a parametric interdependence, extending far beyond simple geometry and form.

A widely accepted definition of BIM implies a parametric design process: i.e. to

> “define objects parametrically. That is, the objects are defined as parameters and relations to other objects, so that if a related object changes, this one will also. Parametric objects automatically re-build themselves according to the

> rules embedded in them. The rules may be simple, requiring a window to be wholly within a wall, and moving the window with the wall, or complex defining size ranges, and detailing, such as the physical connection between a steel beam and column."(Eastman et al., 2011)

The first part of this research work (Markova and Dieckmann, 2012) is focused on the analytical foundation of the proposed design-check approach. It covers the abstract hierarchical structure of the building objects and parameters in the scope of the design-check workflow, the logic trees describing the exact sequence of the design-check loops (complex design-check functions) and proposed additional IfcObjects and IfcPropertySets for the necessary design-check parameters, which are still missing in the IFC 2x4 release.

The current paper is focused on the implementation aspects of the research work. The first section summarises the aims and scope of material use efficiency oriented design, mapped to the parameters that are most relevant for its achievement. In the next section, the practical extension of the missing parameters and the performance of the design-check for a concrete case study are examined on both the IFC schemata level and on the level of proprietary BIM software. In the last section the barriers and restrictions for the practical implementation are discussed.

2. Material Efficiency Related Design Goals

An example of a well optimised material use in a product means:

- A maximum of the input materials can be recovered in a way that enables recycling without downgrade, i.e. the reusability of materials for the same functions in new products.
- Disassembly is designed and performed in a way that enables element reusability in new products.
- It is possible for a maximum of all input materials to be reintroduced into the next use cycle and thereby minimising material waste.

A closer comparison of the product design processes in the building industry and other industries shows the first significant difference, identified as one of the reasons for low material efficiency in the built environment: In contrast to industries achieving a high rate of closed material cycles, explicit design goals towards recyclability (for the reintroduction of materials back into material use cycles), separability (for reusability and recovery), and minimisation of material waste are extremely uncommon in the building design process.

Some of the general material efficiency design principles can be transferred directly onto the building design process. However, there are specifics and

differences between both design processes and end products, which must be taken into account, as for example:

- In contrast to most other products, buildings are mostly unique products – prototypes in essence. This requires a more general approach, allowing for the utilisation of the various existing construction methods, structures, materials, etc.
- Buildings have a longer life than other products, which also means that no "product-line" improvements can be made (i.e. when later product generations are improved based on the weaknesses of the previous). On the one hand, this highlights that design-phase simulation and optimisation for buildings are indispensable. On the other hand, it points to an important difference in the design goal definition: in the case of buildings, design measures towards materials and elements separability and exchangeability (multiple event occurrences during the life cycle) should have a higher priority than end-of-life demolition-oriented measures (crucial for the re-introduction of materials in a global material reuse cycle, but ultimately a onetime occurrence only).
- The material safety aspects (i.e. the presence of hazardous and toxic materials) in buildings have a greater impact on material efficiency than in other products, e.g. if a decade after the product design is finished a widely used material is identified as dangerous due to scientific research, but is located in building elements and structures with low or no chance of exchangeability and separability. Depending on the rate of integration with other elements and structures, the amount of otherwise "healthy" and reusable materials which will have to be removed can exceed the amount of the affected material exponentially.

The two factors "long lasting product" and "new innovation and technology insight" stress the necessity for a detailed documentation and suitable archive-form to attend to the building throughout its life cycle. An IFC-based data model of a building (commonly referred to as a BIM model) is already a possible solution for this specific problem and can therefore be seen as a first step towards the transformation of the built environment into a schedulable secondary resource stock for future use.

The following image (Figure 1) represents a map, connecting the four main design goals for increased material efficiency to possible design parameters, effectively identifying which parameters have the greatest importance for achieving a certain goal.

3. IFC Extension Implementation Study

For the purposes of the IFC extension implementation study, a case study was defined. The aims were: 1) to create a building documentation that includes all substances as subcomponents of the building materials, 2) to enable regular

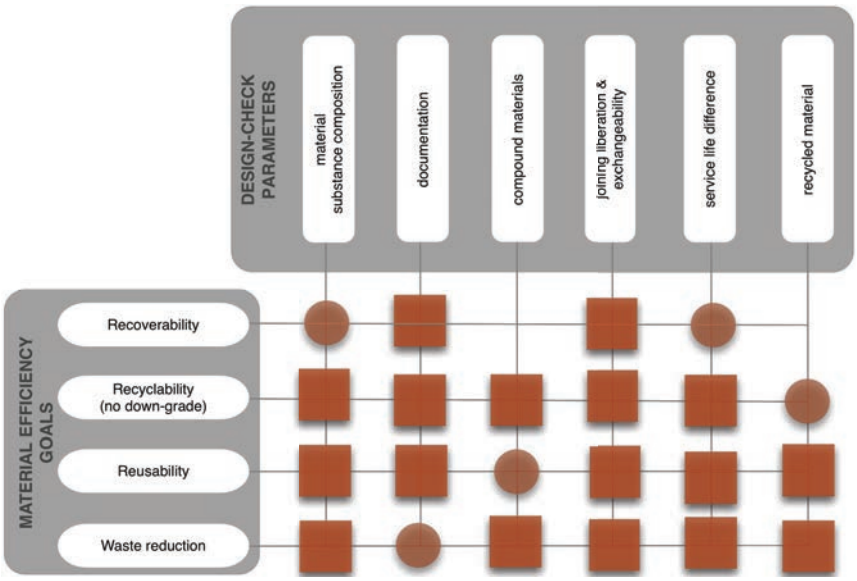

Figure 1. Material-related design goals cross-referenced with possible design parameters. Squares represent crucial interdependencies, while circles represent relevant, yet non-crucial interdependencies.

re-checks of the safety of the materials and 3) to simulate the waste production for cases where some of the affected elements and structures are not exchangeable and separable from each other. The case we researched describes the following hypothetical situation: after a re-check on the building design concept, it turns out that some of the substances in the building have been recently classified as highly toxic. Hence, the substances and their adjacent materials and elements in the building have to be located by means of a design-check. A secondary design-check has to identify the type of connection of the affected element with the surrounding environment and, in case of inseparable connections, give a feedback on the material waste of "healthy" materials and elements.

For the purpose of the design approach, two milestones have to be reached: the "simulation and documentation" and, subsequently, the "optimisation" of the building concept. In the context of this research work, simulation can be understood as a workflow for the static assessment of the initial design concept. As results, it returns recyclability, re-usability and waste production ratios, which are also a subject of documentation. On this level, the designer receives a feedback on his decisions and their impact on the material use efficiency for the given concept. On the next step – "optimisation" – the designer receives support for the solution

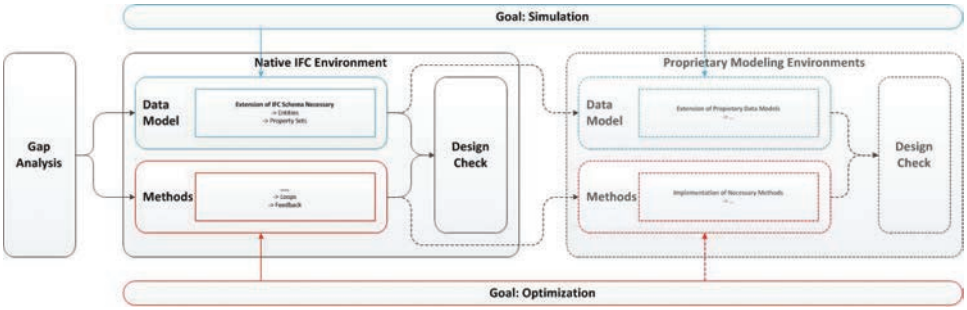

Figure 2. Workflow for a custom IFC extension process and design-check performance on the levels of IFC data models and proprietary BIM software.

of problematic constellations resulting from his initial decisions in order to help him shift the concept towards meeting the pre-defined custom goals. This level implies the restriction or proposition of disadvantageous, or respectively, advantageous actions. For both tasks, functions are defined, which have to be scripted for the corresponding environment (IFC or a proprietary BIM platform) to perform the simulation or the optimisation. The functions underlie a hierarchical design logic flow, which is described in detail in Markova and Dieckmann, 2012 (Markova and Dieckmann, 2012).

Below, the two implementation cases on the level of the IFC data model as well as on the level of proprietary BIM software will be examined in detail.

The following diagram (Figure 2) represents the workflow for the custom IFC extension for the purpose of and the design-check performance.

3.1. DESIGN CHECK ON THE IFC LEVEL

3.1.1. Simulation and documentation

In our case, for the first step, it is enough for the user to manoeuvre on the IFC schemata level only: A full modelling of the building by means of semantic objects implies a full documentation of the objects and their respective properties (which are already defined in the chosen IFC schemata). The simple logic types embedded in IFC are also sufficient for the purpose of checking the building model. Design-checks in the design phase can show if the concept is able to produce the desired building material performance stage (e.g. no materials and substances respond to the property check “hazardous”), while a re-check later in the operation phase of the building can verify whether the desired target state is still valid or has changed. If new information is available, changes can be controlled both

internally for the building project, and externally, if a connection to a current database is maintained.

To perform this check, it is necessary that all parameters (i.e. objects or properties) required for the design-check are described in the chosen IFC release. Mapping the pre-defined parameters to the chosen release either verifies them or delivers a gap to be filled. Missing required IFC objects or properties can be extended via EXPRESS or ifcXML files. To check the operability and consistence of the model in the extended (custom) schemata, a model checking tool like Solibri Model Checker (Solibri, 2012) should be used.

3.1.2. Optimisation

For the next step, more complex functions are required, which not only deliver the result of an action taken or if a change has occurred in the building model, but can also trace the source of the problem and report it to the user (e.g. the type and location of unsolvable connections between affected elements). Moreover, specific user "behaviour" can be fully restricted (e.g. connecting elements inseparably that have a significant difference in expected service life). One possible tool that allows to script and perform a user-defined design check on an IFC Model is the IFC WebServer (Ismail, 2012). It offers a high degree of freedom in the choice of the IFC version for the input model (all official IFC versions, as well as customised versions) and an integrated interface for scriptable custom design-check functions (based on the scripting language Ruby). The final results are currently delivered in the form of reports (direct visualisation in the model still is work in progress) and can be filtered and exported in various formats (e.g. IFC, COLLADA, HTML, XML etc).

3.2. DESIGN CHECK IN PROPRIETARY BIM SOFTWARE

3.2.1. Simulation and documentation

The most natural way to perform a design-check on the model in progress is directly in the modelling environment itself. Theoretically, the BIM software of choice operates with the full range of objects in the chosen IFC schemata or its IFC interface will at least allow for the import of new objects, existing in the full range of that chosen IFC release.

To extend the semantic content in a specific scenario (e.g. project or modelling environment), a rule framework should be followed, which defines the behaviour of the new IFC objects in this specific environment. The standardised framework created by buildingSMART is the Model View Definition (MVD), which places the IFC object first in the specific scenario and determines its functions and behaviour

(exchange and view requirements and definitions) (Chipman, 2012; Chipman et al., 2012), i.e. the MVD defines how (existing or new) property sets, properties and simple logic types refer to the new object and vice versa. When an EXPRESS file of the new IFC entity is available, tools like buildingSMART's IfcDoc support the generation of the full MVD documentation (including EXPRESS-g, listings, change logs etc.).

Once the semantic model in the modelling environment has been extended, the user can perform the "documentation and simulation" step for any project, building and building specifications. Moreover, the changes in the course of the project in the modelling environment are parametrically correlated, i.e. any geometrical, material etc. changes of the building model will affect the documentation and the simulation result.

3.2.2. Optimisation

Very complex design-check functions should be scripted utilizing the API of the respective BIM software (usually in VB, C#, Python or another object-based language). The advantage of programming an add-on within the modelling software-tool of own choice is that it facilitates a seamless workflow within a single software environment from modelling to simulation to optimisation. Also, the algorithms can be applied to any other (new or older) models and the add-on (if the vendor offers the possibility for it) can be shared in a community. It is also much less work than creating stand-alone tools and does not require the purchase of additional software.

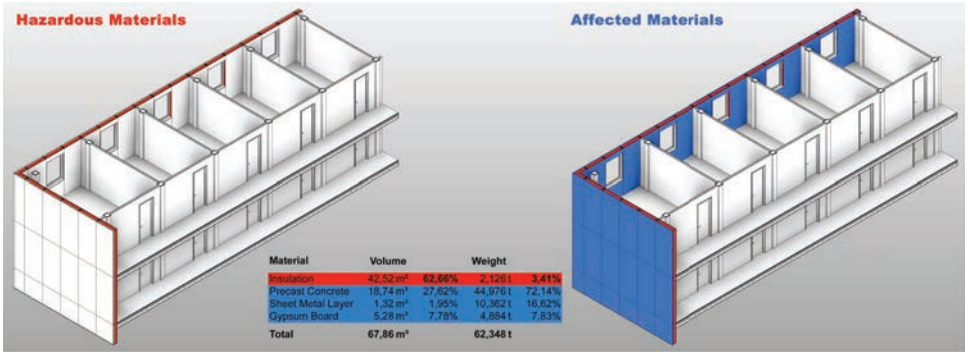

Figure 3. Use case example results: The identification of a hazardous substance in the insulation would cause the disposal of a significant amount of "healthy" materials due to unsolvable connections between elements and material layers.

4. Discussion: Challenges, Barriers and Restrictions

The workflows proposed above and all of their workflow steps correspond to the established standards and methods for working with IFC and BIM. However, the implementation in practice is to some extent problematic and in some cases rather restricted.

During the course of this implementation study, we identified as a major problem the necessity for a profound knowledge in programming and programming environments, as well as being able to work in a variety of programming languages for the user to be able to extend the IFC schemata in a functional and operable way. We believe that this is not reasonable for an average architect, designer or engineer. If a user does have these skills, though, the barriers described below are conquerable (even if the workflow still remains increasingly ineffective and time consuming).

Even though IFC is an open source standard, the practical implementation of the extension is not fully customisable yet. This is due to the fact that even if extensions and MVDs are theoretically manageable by a single user, the standardised way for practical implementation is set to pass through a certification phase by buildingSMART. This, of course, is indispensable for reasons of safety, functionality and quality control. However, it is a significant barrier for research oriented usage and therefore for the wider adoption and understanding of the environment.

With its special focus on materials and their properties, our work was significantly restricted by the fact that the BIM tools we used for the implementation study so far have not embedded the IFC material level to full extent. Therefore, we experienced very limited options for experimenting on this level in a generic way.

However, it is important to underline that even if we recognise the necessity of further development to make the utilisation and user-defined adaptation of both data format and BIM tools more open and user-friendly, we are convinced that increased design and building performance will be based on a unified data standard for all design participants and a semantic, parametric building design.

References

Chipman, T.: 2012, *IFCDOC Usage Guide*, Model Support Group (MSG), BuildingSMART International.

Chipman, T., Liebich, T. and Weise, M.: 2012, *mvdXML: Specification of a standardized format to define and exchange Model View Definitions with Exchange Requirements and Validation Rules*, Model Support Group (MSG, BuildingSMART International.

Eastman, C., Teicholz, P., Sacks, R. and Liston, K.: 2011, *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractor*, John Wiley, 622.

Ismail, A.: 2012, “IFCWebServer: Web-based BIM data model server and online viewer”. Available from: <http://www.ifcwebserver.org> (accessed 25 November 2012).

Larsen, K. E., Lattke, F., Ott, S. and Winter, S.: 2011, Surveying and digital workflow in energy performance retrofit projects using prefabricated elements, *Automation in Construction*, **20**(8), 999–1011.

Markova, S. and Dieckmann, A.: 2012, An IFC based design check approach for The optimiSation of material efficiency in the built environment, *CAADRIA 2012: Beyond Codes & Pixels*, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) and Hindustan Institute of Technology & Science, Chennai, India.

Solibri, I.: 2012, Solibri Model Checker.

Walsh, B.: 2011, Why the Real Victim of Overpopulation Will Be the Environment, *TIME*, 26 October 2011.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 23–32. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

A THOUSAND BIM

A rapid value-simulation approach to developing a BIM tool for supporting collaboration during schematic design

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Abstract. A typical architectural design project proceeds as collaboration among professionals who have different expertise, values and priorities. The collaboration is needed to make designs both rich yet feasible, but the professionally different ways of thinking can also be a block on the way of design development. This paper takes the example of the relationship between developers and architects, who tend to have different evaluation criteria, methods, and processes. A BIM-based tool, *A Thousand BIM*, is introduced as a means to quickly generate possible building typologies on a given project site, with computation of expected total values expressed in simple financial terms. Its aim is to help a group of heterogeneous professionals to communicate in the same language, articulate criteria and priorities in multiple perspectives, and share rapidly simulated evaluations of schematic design variations. The implemented evaluation process considers construction cost per square foot, land value, and sustainability as well as other soft design values such as views and accessibility. It can take various market data as inputs to cost calculation, and the weight to each of the design values is dynamically adjustable. A professional can explicitly set them, and share the criteria, priorities, and results of value simulations with others in an enhanced collaborative process.

Keywords. BIM; pro-forma; design collaboration; value simulation.

1. Backgrounds

There are many barriers that block collaboration among professionals in the building and design industries. A quintessential barrier may not be a physical or technological one; rather it may be epistemological (Turkle and Papert, 1990). The different ways of thinking that professionals have may make them reluctant to join

in design collaborations (Root et al., 1999; Holzer, 2009). During the design process, multi-disciplinary professionals may have different evaluation criteria, and understanding these differences is the key to a successful collaboration.

Architecture, engineering, and construction (A/E/C) industries have studied how to improve design collaborations for many years. Researchers developed virtual and physical platforms for a collaborative environment (Wang and Dunston, 2008; Rosenman et al., 2007). Improving communications by utilizing wireless and IT technology is accepted as an important factor in maintaining the quality of collaboration (Zurita et al., 2008). Providing shareable data format and online-storage is highlighted while building information modeling (BIM) technology is spreading widely (Cerovsek 2011; Azhar, 2011). Although professionals accept the significance of human aspects in collaborations, there are few studies on this subject (Arias et al., 2000; Xue et al., 2012; Singh et al., 2011).

Instead of understanding a value as an objective or universal measure, a human understands a value in relation to his profession, culture, or beliefs (Berger and Luckmann, 1967; Deleuze and Guattari, 1987; Fideler, 2000). Value is not measured; rather, it may be created in a thousand different ways by who measures it (Deleuze, 2006). In pondering a true value, it is more important to understand how humans create it than what the value is. A single design could be measured in various ways and have multiple values simultaneously. The value of a design can be fully understood only when multiple perspectives from various professionals are considered. Architects may evaluate a design from the balance between its forms and functions; developers may prioritize its financial values, such as net operating income or the land's residual value; and end-users may consider the maintenance cost or the flexibility of space. In a conventional design project, it usually takes tremendous time to evaluate a design proposal through involvement of different professionals and form an aggregate judgement. Advanced building information modelling tools today present a new potential to alleviate this situation.

2. Extending BIM for Enhanced Collaboration

Use of BIM contributes to improved productivity of both the design and construction phases in many respects. BIM supports fast changes of design by providing parametric tools and component libraries. These tools reduce laborious reworking processes that are inevitable with conventional CAD tools. Likewise the use of intelligent, information-rich components in BIM makes it easy to check collisions of elements, construction errors, and any omissions in documents, and helps to identify many problems during the early design phase. Also, BIM's cost calculation tool, such as material take-off, allows designers to develop a scheme with a financially reasonable strategy. These benefits of using BIM combined with

the simulation and evaluation of building performance such as energy consumption and structure promise to improve the return on investment (Shelden, 2009).

On the other hand, this large load and variety of information that BIM proceeds to rapidly build and process for a design project can become the source of problems for its human participants. For instance, the use of BIM anticipates that designers will include such considerations as fabrication methods, construction costs, and programmatic valuations from the early design phase. Controlling, keeping track of, and paying attention to each one of them throughout the development is a cognitive process different from a traditional one, where an initially sketched form is gradually elaborated with more information accumulated at each step of the way. The situation can become more difficult to comprehend when each of multiple professionals in a project simultaneously and independently generates project details, simulations, and evaluations from a different professional perspective. Producing a large amount of information does not always help unless there is a comprehensive way to grasp the totality of the project and to allow participants to understand and appreciate information across the professional boundaries.

This paper introduces a tool that is intended to enhance collaboration among a group of heterogeneous professionals by helping them to communicate in the same language, articulate criteria and priorities from multiple perspectives, and share simulated evaluations of schematic design variations. The proposed tool, *A Thousand BIM*, takes advantage of the versatile power of BIM, and extends it to accommodate epistemological pluralism and cross-disciplinary interactions. The tool quickly computes and generates possible building typologies on a given project site with visualization of expected total values in financial terms. For instance, it automates the process of computing a pro-forma financial statement for architects and developers during the design process, and helps them to quickly decide whether a proposed project is worth investigating.

3. Implementation of *A Thousand BIM*

The system is composed of four modules: data feeder, form generator, analysis visualizer, and financial evaluator. The overall workflow follows Mitchell's (1977) genetic algorithm in architectural design, which is composed of form generation, evaluation, and selection.

The first module (the data feeder in Figure 1) imports an XML document with basic project information such as location, construction cost per square foot, site, climate, energy cost, urban context, and market statistics, which become the basis for calculating the land's residual value and net operating income. The data can be obtained by collecting information manually or purchasing a service from real-estate market data providers.

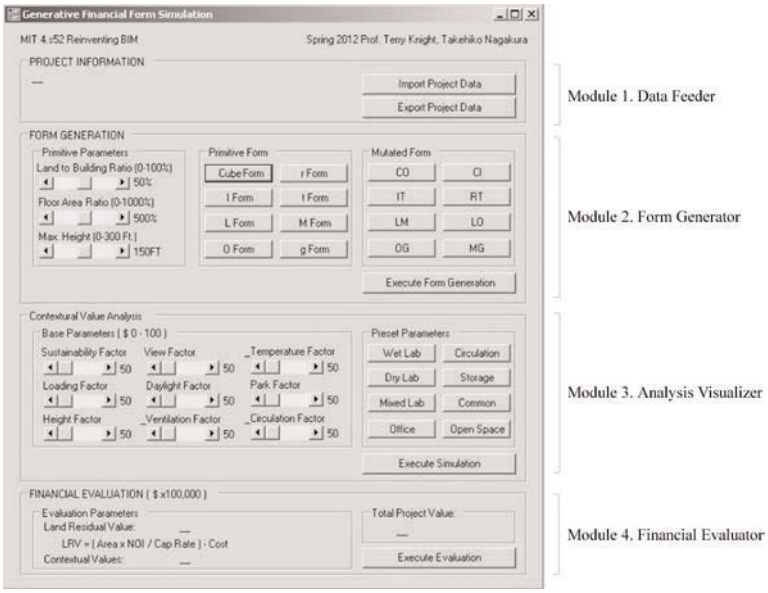

Figure 1. The interface of the proposed tool.

Then a user makes selections from basic typologies of plan such as Cube-shaped, L-shaped, I-shaped, and O-shaped ones, and specifies gross floor area, maximum building height, and land-to-building ratio. The form generator (module 2 in Figure 1) produces variations of buildings that satisfy the required architectural program as well as their mutated forms that are random combinations of two plan typologies (Figure 2). Then the building form is subdivided into small space units called *rooms*.

The key component of this system is the analysis visualizer (module 3 in Figure 1). For each room, the tool computes the weighted score of each design value such as view, accessibility, sustainability, ceiling height, daylight, temperature, ventilation, parking proximity, and loading convenience, and adds them up. It then shows the pattern of aggregated room values distributed over the whole building. This process accounts for rooms with good view that many hotels near tourist attractions would charge higher, and rooms with easy access and sustainable features that clients of laboratories are willing to pay additional to rent. Accordingly, the tool assigns those desirable rooms with suitable functions while interpreting other rooms as space for circulation and services.

This module implements an artificial neural network algorithm inspired by the self-organizing map (Kohonen, 1990). It is a computational model of biological

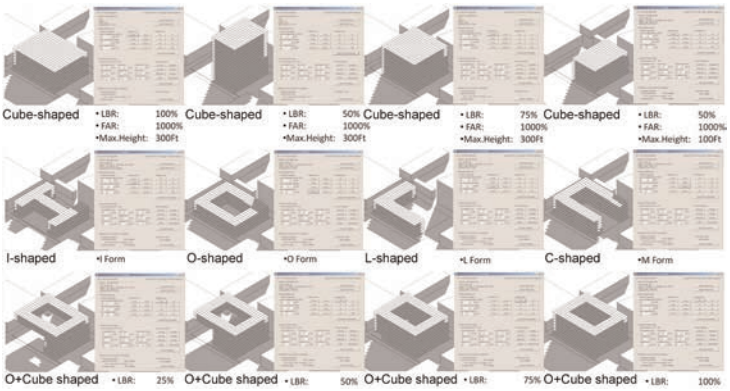

Figure 2. Generation of basic and mutated (combined) building forms.

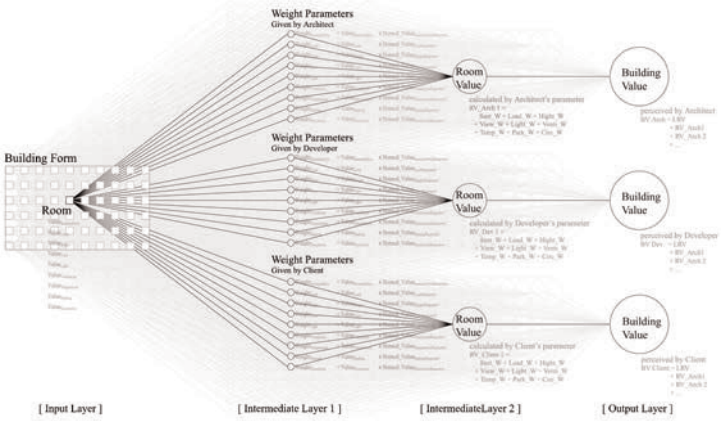

Figure 3. An artificial neural network algorithm to calculate total building values from three different perspectives: an architect, a developer, and a client.

neural networks composed of an input layer, intermediate layers, and an output layer. The input layer accepts initial data and passes them to implicit intermediate layers. Their initial values are manipulated there, reconstructed into new values, and summed up to become the total value of an output node (Figure 3).

$$\text{WeightedScore}_{\text{DesignParameter}} = \text{NormalizedScore}_{\text{DesignParameter}} \times \text{InputWeight}_{\text{DesignParameter}} \quad (1)$$

$$\text{Room_Value}_i = \sum_{j=1}^{\textit{Number of Parameters}} \text{WeightedScore}_{\text{DesignParameter-j}} \quad (2)$$

$$\text{Building_Value}_k = \text{Land_Residual_Value} + \sum_{n=1}^{m} \text{Room_Value}_n \quad (3)$$

At the beginning, each score of design values such as views and accessibility is calculated through a simple algorithm that utilizes the distance between a room's location and surrounding urban elements such as nearby buildings and landmarks (Figure 4). Resulting scores are stored as metadata attached to the room and become the input of a neural network algorithm. The process then goes through two intermediate layers of computation. In its first layer, attribute scores are normalized and multiplied by corresponding input weight specified by a user. Then in the second layer, the results are summed up to be the value of a room.

Finally, in the financial evaluator in Figure 1, these room-values of a building are summed and added to the land's residual value. This total value represents a design judgement expressed in financial terms, and is the result of a single epoch of one professional's value simulation. The simulation process can be repeated by the same person as well as by different professionals in a collaborative project. The criteria and priorities adjusted for repeated simulations are transparent and accessible to all participants to share, open up one professional's judgement process to others, and let the participants see possibilities beyond what is usually excluded by their own professional cultures. Various professionals gain opportunities to learn each other.

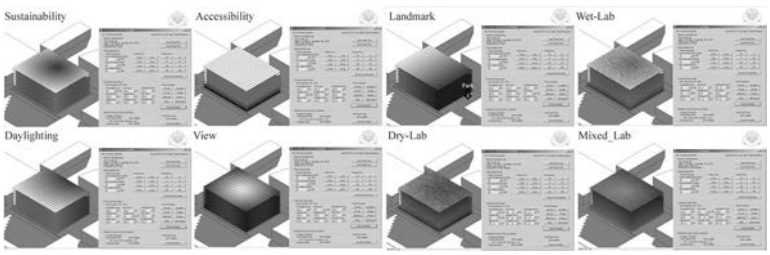

Figure 4. Results of space analysis and their visualized patterns for individual design values (sustainability, accessibility, landmark, day lighting, view), as well as for their weighted sets (wet-lab, dry-lab, mixed-use lab). A grayscale value corresponds to the fitness level of a room for an attribute. The dark gray area is where the room fits well for a selected attribute.

4. Application Example

To illustrate the potentials and limitations of the tool, a comparative study with an existing building project is conducted. The selected project is a 278,000-square-foot research laboratory. One of its main design strategies is energy optimization using a varying facade design that balances solar heat gain in winter and shading in summer while preserving views. Another is the central void space that supports retail units on the ground and works as a center of collaborative activities (Figure 5, left).

Using the same site and context as the existing building, three simulations for a simple box form (building typology for the Cube-shaped) with differently weighted sets of design values for a dry-lab, wet-lab, and mixed-use lab were conducted. A dry-lab, such as a computer lab and office space, usually requires high-level parameters for design values of view and daylight. A wet-lab, such as a chemical lab, has relatively high operation cost and material traffic, and requires high-level parameters for the design values of sustainability, loading convenience, temperature and ventilation. Parameters for a mixed-use lab are set between these two laboratory settings.

The comparative study shows coincidence between the actual building design and a simulation result with the dry-lab design value setting. As shown in the right image of Figure 5, the tool identifies the locations suitable for lab spaces near the building perimeters and at its high floors (the dark gray areas in Figure 5). It also identifies the ground floor and the central area of the building as the supporting area, including the common space and circulation (the light gray areas in Figure 5). In comparison, the existing building has a retail space on the ground floor, atrium in the center, and laboratory and office space on building perimeters. Thus the simulation indicates that the designers considered their main target clients as dry-lab users such as large IT companies and start-ups, as other buildings do near this building site. In contrast, if we use the wet-lab design value setting, the tool

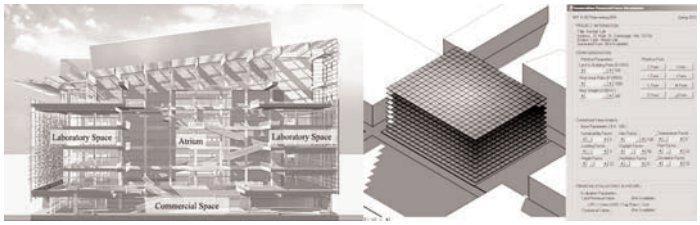

Figure 5. The sectional diagram of the existing research lab (left) and the pattern analysis of a Cube-shaped form with design value setting for dry-lab (right). This building in Cambridge, Massachusetts, was designed by CO Architects of Los Angeles and constructed in 2009.

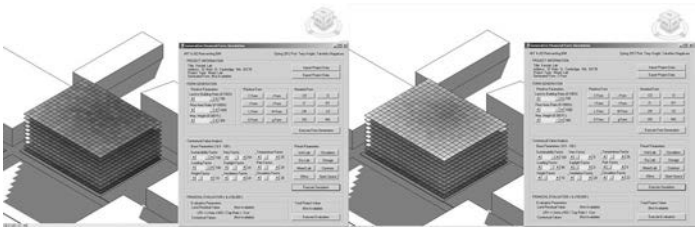

Figure 6. Simulation results with design values for a mixed-use lab (left) and a wet-lab (right).

identifies the appropriate locations of the laboratory space on low floors and in the central space of the building, and all other supporting areas on high floors and near building perimeters (Figure 6, right). Or the use of the design value setting for a mixed-use lab would result differently in a cluster of wet-lab spaces on the first two floors, dry-lab space distributed on high floors near the south facade and nearby landmarks, and the retail and circulation space relocated around the building perimeters, as shown in the left image of Figure 6.

If the architect and the developer had used this tool during the early design stage, they could have quickly compared the suitable room layouts and their total financial values for those three alternative settings, dry-lab, wet-lab or mixed-use lab. Weights of some of those design values, such as view may be further fine-tuned to reflect each professional's perspective in the successive iterations of value simulation. Other possible applications include comparisons between different building typologies on the same site, or even comparisons between projects at different candidate locations.

5. Conclusion

A Thousand BIM generates various building typologies and computes their values expressed in financial terms that are based on user-selected and –weighed evaluation parameters. This process of value simulation requires heavy information processing. The combined use of efficient computational algorithms and the framework of the robust BIM environment have demonstrated a potential to deliver a practical solution with sufficiently rapid execution. -

This tool is intended to promote collaborations among multi-disciplinary professionals who have different expertise, values, and priorities. For instance, typical design collaboration between an architect and a developer entails a sequential process in which the developer gets a chance to evaluate design feasibility only after a spatial design is proposed by the architect. The architect then may update the initial design after the developer gives feedbacks. Throughout, the process and

rationale of one professional tends to stay opaque to the other professional, cognitive barriers may engender reluctance of participants, and a respect for difference may give way to suspicion.

The proposed tool is expected to combine such design/evaluation iterations into a more integrated and rapid concurrent process. Using the tool allows any participant of a project to explore options for varied architectural forms and programs, and access the results of value simulation with rapid feed-back. The criteria and priorities in the evaluation process are transparent and accessible for all participants of a team. This lets participants open up the professional processes to others, and see possibilities of judgement beyond the usual bounds of their own professional cultures. This kind of tool also should be helpful for an individual designer to keep a grip on the valuation of evolving design that goes through countless changes and elaborations from an initial schematic state.

The study presented here has been fashioned so as to set up a laboratory test, and several future extensions are immediately identified. This implementation is confined to the use of a limited, fixed number of kinds of design values such as land value, sustainability, view and accessibility. Since architectural design projects typically deploy a variety of other controlling design values such as openness, privacy, security, maintenance, construction duration, and many more, development of a flexible, open-ended system is worth exploring to allow professionals in order to add and compute with a contingent set of diverse design values. Algorithmic development for computing each of those is a challenge. Also, additional end-user studies are necessary to illuminate how such a tool actually is exploited by professionals other than architects and developers, and affects on their collaboration. This leads to research on identifying effective interfaces, monitoring end-user experience, and measuring end-user performance. While the current tool is calibrated to a building design for commercial property with spatial units such as hotel, office, rental lab, and apartments, consideration of other types such as institutional buildings and houses is critical in understanding the potentials and the limitations of this approach.

In summary, the main contributions of this study include: 1) introduction of a novel platform tool that lets each participant explicitly set criteria and priorities of a design project, automates generation of schematic design variations, and performs value simulation as feedback to the participant, and 2) demonstration of implementing efficient computational algorithms for the typological design generation and the value simulation process in the context of architectural design.

Combined, they form a strategy for enhanced collaborations among different professionals in a multi-disciplinary design project. Time-consuming, reluctant, and opaque multi-stage collaboration can be transformed into a rapidly shared, transparent, and concurrent process of willing participants.

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References

Arias, E., Eden, H., Fischer, G., Gorman, A. and Scharff, E.: 2000, Transcending the individual human mind - Creating shared understanding through collaborative design, *ACM Trans. Comput.-Hum. Interact.*, **7**(1), 84–113.

Azhar, S.: 2011, Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry, *Leadership and Management in Engineering*, **11**(3), 241–252.

Berger, P. L. and Luckmann, T.: 1967, *The Social Construction of Reality: A Treatise in the Sociology of Knowledge*, Anchor.

Cerovsek, T.: 2011, A review and outlook for a "Building Information Model" (BIM): A multi-standpoint framework for technological development, *Advanced Engineering Informatics*, **25**(2), 224–244.

Deleuze, G. and Guattari, F.: 1987, *A Thousand Plateaus: Capitalism and Schizophrenia*, University of Minnesota Press.

Fideler, D.: 2000, *Alexandria 5: The Journal of Western Cosmological Traditions*, Phanes Press.

Holzer, D.: 2009, Sense-making across collaborating disciplines in the early stages of architectural design, Dissertation, RMIT University, Australia.

Kohonen, T.: 1990. The self-organizing map, *Proceedings of the IEEE* , **78**(9), 1464-1480.

Mitchell, W. J.: 1977, *Computer-aided architectural design*, Petrocelli/Charter.

Rosenman, M. A., Smith, G., Maher, M. L., Ding, L. and Marchant, D.: 2007, Multidisciplinary collaborative design in virtual environments, *Automation in Construction*, **16**(1), 37–44.

Root, D., Fernie, S. and Baldwin, A.: 1999, The languages of Product and Service: Barriers to the Integration of Construction and Design, *Proceedings of the 15th ARCOM Conference*, Liverpool John Moores University, Liverpool, 181–190.

Shelden, D.: 2009, Information Modeling as a Paradigm Shift, *Architectural Design*, **79**(2), 80–83.

Singh, V., Gu, N. and Wang, X.: 2011, A theoretical framework of a BIM-based multi-disciplinary collaboration platform, *Automation in Construction*, **20**(2), 134–144.

Turkle, S. and Papert, S.: 1990, Epistemological Pluralism: Styles and Voices within the Computer Culture, *Signs*, **16**(1), 128–157.

Wang, X. and Dunston, P. S.: 2008. User perspectives on mixed reality tabletop visualization for face-to-face collaborative design review. *Automation in Construction*, **17**(4), 399–412.

Xue, X., Shen, Q., Fan, H., Li, H. and Fan, S.: 2012, IT supported collaborative work in A/E/C projects: A ten-year review, *Automation in Construction*, **21**, 1-9.

Zurita, G., Baloian, N. and Baytelman, F.: 2008, A collaborative face-to-face design support system based on sketching and gesturing, *Advanced Engineering Informatics*, **22**(3), 340–349.

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PARAMETERIZE URBAN DESIGN CODES WITH BIM AND OBJECT-ORIENTED PROGRAMMING

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Abstract. There has been a significant need for the new urban design apparatus that carries out performance analyses of the urban models, since the code reform movements focused on the sustainable urban developments. This research explores the use of parametric Building Information Modeling to enable stakeholders to intuitively understand the implications and consequences of urban design codes. We investigate whether key regulations can be captured as algorithms and ontologies in parametric BIM and Object-Oriented Programming. Then we present our prototype of parametric urban models in a BIM platform that explains (1) the extent which urban design code information can be parameterized in BIM and (2) the methods how parametric models can hold code information. The results show that our prototype enables real-time manipulations of code requirements and interactive visualization of code allowances.

Keywords. Parametric modelling; BIM; Object-Oriented Programming; urban design codes.

1. Complex Datasets and Tools in Urban Design

Urban design for community scale developments has been carried out by using complex datasets that are still either digital or analogue. For instance, socio economic and environmental data as well as land-use and zoning information can be obtained from Geographical Information System (GIS) data. Other regulatory requirements are provided in text-based documents. Subdivision plans, created by civil engineers, are distributed in the CAD format generally. Citizen's inputs from the design charrette are stored in sketches and documents.

In this circumstance, designers juxtapose and synthesize such data to understand what they imply. They create urban models by using a series of computer tools; CAD tools for site plans and three dimensional models; rendering software

for perspectives; spread sheets for feasibility assessments; and energy simulation tools for environmental footprint analyses.

GIS has been used for the repository of natural resources and infrastructures. Urban design regulations are partially stored in GIS data such as zoning and land use maps. Three dimensional design codes also are not included in GIS; in the GIS land use map, a mixed-use zone is displayed with a specific colour code, but further information can be found in the local zoning code document. In addition, inaccurate spatial data of GIS can be used in design process after calibration processes. For instance, when the GIS shape file of the land use layer is exported to the DWG format, inaccurate lines and incomplete polygons can be found. They can be used after considerable post-processing.

This complex use of datasets and tools in urban design can impede interactive feedbacks and rapid design changes. Majority of urban design supportive tools have been developed to scope with interactive visualization and design alternatives, but still there is a significant need for the new urban design platforms for reliable urban modelling, comprehensive data managements, and interactive performance analysis (Barnett, 2011).

2. Modelling of Urban Design Codes

2.1. CODES AND URBAN DESIGN

Urban design codes provide a framework that governs design allowance for various urban design components such as open spaces, public spaces, and buildings. In the United States, recent codes have focused on physical urban form of open space, streets, buildings, and other physical design elements, while conventional codes often focused upon building function and scale (Barnett, 2011; Walters, 2007). However, it has been argued that the contemporary urban design codes employ highly structured code components and prescriptive provisions, and that there are complex interrelationships among such components and provisions (Kim et al., 2011).

2.2. PARAMETRIC MODELLING AND OBJECT-ORIENTED PROGRAMMING IN BIM

BIM has been developed to support the Architectural Engineering Construction (AEC) industry. BIM ties all the building components with imbedded information to create a building product model (Eastman et al., 2011; Sacks et al., 2004). In addition, BIM facilitates communication of design intentions, and coordinates construction processes using BIM's shared database. Parametric modelling

capabilities in BIM provide mechanisms to map knowledge-based rules into BIM objects, enabling automatic manipulations and semantically-rich model generations (Sacks, Eastman, & Lee 2004). In addition, Application Programming Interface (API) BIM authoring tools provide can support application customization and software development.

This chapter describes a framework of how the parametric BIM modelling can build code components and key provisions, how the API in BIM can establish the interrelationships among them, and how the parametric code models and the applications can communicate.

2.3. BEHAVIORS AND ATTRIBUTES OF BIM OBJECTS

BIM objects are the representation of building components such as walls, roofs, and floors. BIM objects have functionalities that can respond to object manipulations, which can be found in the real-world. These functionalities are behaviours of BIM objects. In BIM objects, attributes are accessed through the parameters. For instance, the wall object in BIM can be moved, rotated, and extended as parametric definitions are changed, but only predefined behaviors can be performed. Most BIM objects represent specific building components and limited behaviors, so they are not appropriate for our parametric code modelling.

User definable objects in BIM allow users to create a BIM object with customized behaviours and attributes that can control geometric representations and properties. The parametric urban code model is created using the user definable objects, so it is required to understand what kinds of behaviours and attributes need to be built and how they can be modelled in BIM.

2.4. MAPPING URBAN DESIGN CODES INTO BIM OBJECTS

Clarifying urban design behaviours and their attributes is the first step of our implementation. For instance, code provisions can secure a minimum open space area by controlling building topologies with maximum widths, depths, and heights as well as building dispositions with setbacks and built-to-lines. In this case, controlling building dimensions and dispositions can be understood as urban design behaviours. In addition, the required values, such as a distance from the property line and building heights, can be defined as attributes. This attributes can be modelled in parameters in BIM objects.

Urban design behaviour can be interpreted as diverse parametric modelling behaviours, which dramatically affects the modelling procedure of BIM objects. For instance, a setback control in the code can push a building façade to the

designated position. On the other hand, an invisible setback line can cut out the building mass outside of the designated position. Furthermore, a void mass can be created to subtract a solid mass outside of the setback lines. Three modelling approaches can present setback requirements, but each one needs to have different behaviour.

3. Experiments

The first implementation step is (1) creating BIM objects that can represent a set of code components and (2) representing the associations among the objects and their parameters using parametric modelling features in BIM. The next step is (3) developing analytical.

In our experiments, we use Revit Architecture as a parametric BIM development interface, Revit API as an application development platform, and C# as an OOP language. With the parametric modelling features in BIM, a BIM object can store information as parameters, the elements of the object can be manipulated according to any parametric values, and relationships among objects can be established. Revit API enables access the model data, generate new elements, edit existing elements, define customized functions and user interfaces, conduct analysis, as well as produce model documents. OOP is an advanced approach in software development, enabling rapid development, high maintainability, and high performance based on a set of rules for operating objects (Cox, 1986; Pinson, 1988).

3.1. DEFINE A PARAMETER SET

Based on a review of existing zoning code, we decided a list of urban components and their parameters that are modelled in the parametric code model. We reviewed existing zoning codes in the United States that outline specific urban form and building design by using (1) Transect and (2) prescriptive provisions. Transect is an urban planning strategy that outlines the hierarchical development scale from suburban to urban cores (Hascic 2006). Each transect zone controls the degree of developments by using particular sets of provisions. Prescriptive zoning codes, in comparison with traditional zoning codes, include more regulatory information of form and geometry (Ben-Joseph 2009). These prescriptive codes intend to reshape urban space and public realm by controlling private developments. They employ built-to-lines to designate the location of the building front facade and siting requirements to designate three dimensional building disposition allowances. In our test case model, following parameters are included.

Table 1. Parameters in the code models.

Categories	Parameters	Descriptions	Units
Parcel (Property)	Transect code	Zoning codes from rural to urban	N/A
	Open space ratio	The percentage of open space to the property area	%
	Open space area	The lot area excluding structures	ft^2
	Property area	The property area	ft^2
Building	Footprint area	The building ground covered area	ft^2
	Gross floor area	Total floor area of the building	ft^2
	Setback	The distance from the property line to the building envelop	ft.
	Depth	Building depth of the building	ft.
	Building Height (Ground floor)	The first floor height from slab to slab	ft.
	Building Height (Upper floor)	The upper floor height from slab to slab	ft.
	Number of floors	The floor number of the building	N/A
Parking	Required parking number	Total parking numbers according to the building total floor area and the use	N/A
	Number of street parking	The number of on-street parking spaces	N/A
	Available footprint area	The maximum area for the parking structure exclude buildings and open space	ft^2
	Planned footprint area	The parking ground covered area	ft^2
	Parking space area per car	The parking lot area for one car	ft^2
	Number of floors	The floor numbers of the parking structure	N/A
	Building height	The height of the parking structure	ft.
	Distance from buildings	The distance from the buildings	ft.
	Distance from property lines	The distance from the property	ft.

3.2. CREATE PARAMETRIC CODE MODELS

In the development of the parametric code models, three major urban components are implemented; parcel, building, and parking.

The parcel component holds topology information and regulatory information that can outline open spaces, development capacity, building dispositions, and building envelopes. For instance, the minimum ratio of open space to the property

area and maximum area of building footprints are described in most code provisions; therefore, the parcel area determines an open space area as well as footprint area of buildings and parking structures. In addition, parcel topology determines some required building lines where the building front façade shall be built or where the main building shall be located. Building setback lines can be generated from the parcel topology.

The building component holds topology information and development capacity information. Prescriptive transect zoning codes specify three dimensional building configurations including building heights, the number of floors, as well as roof and attic heights. The building disposition information of the parcel component should be applied to the building component; required building lines and setback lines of parcel components formulate the building envelope in our modelling process.

The parking component holds parking structure topology information and parking regulatory information. In general, several parking provisions such as the total parking numbers, setbacks, and entrance locations are described in the zoning codes. For instance, the urban design codes (City of Ventura 2007, City of Peoria 2010) designates that a residential building shall provide one parking space for every 1,500 square feet floor. This provision implies that the total parking number can be calculated from the building component. In this circumstance, the parameter values of the parking component can be decided through complex calculations using multiple values from the parcel and the building component.

3.3. MODELLING OF THE ASSOCIATIONS AMONG COMPONENTS AND THEIR PARAMETERS

A set of code components and provisions can be parameterized into a BIM object in diverse ways, but presenting hierarchical associations among the components and their parameters can ease the complexity in the urban model creation.

For instance, a code model can present multiple building and parcel components as shown in the Figure 1. All parameters are included in the same model, so the associations across the multiple components are easily stored in parameter equations. However, the amount of parameter information is too large to be applied for the large scale urban code models having multiple code components. If this approach were applied for the parameter lists in the Table 1, the code model can have more than twenty parameters. If the BIM object had twenty properties, more than four hundred parameters need to be handled. Eventually, this approach would increase the complexity of the BIM object.

In our experiments (Figure 2), we implemented the parametric urban code model having open spaces, buildings, and parking structures by following steps.

- A parking component is hosted by a building component.

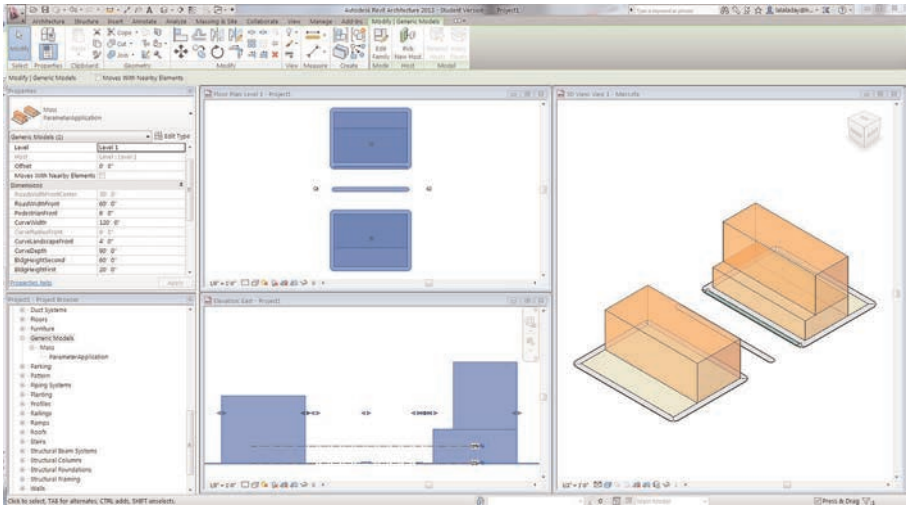

Figure 1. A test case model comprised of a single BIM object.

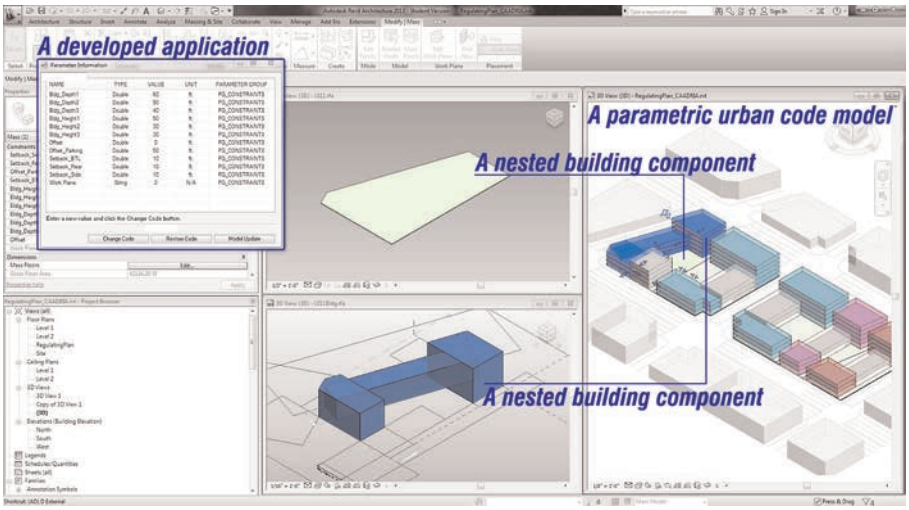

Figure 2. A parametric urban code model hosting multiple parametric code components.

- A building component is hosted by a parcel component.
- A BIM object consists of a parcel component that hosts a building and a parking component. This single object presents one parcel. We call this BIM object as a parametric code object (Figure 2).
- An urban model hosts multiple parametric code objects. We call this urban model as a parametric urban code model (Figure 2).

By nesting multiple code objects with the same hierarchy of zoning code components, the parametric urban code model can store parameters in the various but the most relevant depositories; Transects and open space requirements are modelled in the parcel object, the building geometry requirements are imbedded in building objects, and parking parameters are modelled in parking objects.

3.4. DEVELOP ANALYTICAL APPLICATIONS

The parametric modelling capabilities in BIM enable users to assign new parametric values from the user interface. However, some associations across multiple code objects cannot be stored in parameter equations because a BIM object cannot automatically and intelligently recognize the parameters within other BIM object.

An example is Floor Area Ratio (F.A.R.), a ratio of the total floor area of the buildings to the property area. To obtain this value from the parametric urban code model, two values are needed; gross floor area and property area. The gross floor area can be read from the building object and the property area can be read from the parcel object. Another example is the maximum building footprint area. In general, a certain ratio of the property area is allowed for the building footprint area. To do so, the property area and the allowed ratio need to be collected from the parcel object, and it can be transferred to the building object. However, the building object in the model cannot read parameters from other objects.

In this circumstance, such associations across the entire code objects can be established by external applications written in Revit API and OOP in C#. This chapter describes how our developing applications can access the information of the parametric code objects, formulate new values using multiple parameters, and transfer the new values to the code objects.

Following code examples show the Revit API that can (1) read parameters of the entire model, (2) calculate F.A.R. values using given parameters, and (3) display information to the user interface.

The first step is selecting a parcel component in the Revit user interface to read its name as shown in the Figure 3. The collected values will be used for locating a correspondent building component and a parking component from the entire urban code model. To do so, we retrieve the ‘name’ value of the ‘Parameters’ class of the parcel component. After that, other internal variables of the code name and the parcel name are defined. A loop construct of foreach is used to apply the same process to the entire parcels.

Next step in Figure 4 is collecting required parameter values for the density calculation from the selections. The property area, transect zoning codes, and the parcel name are collected and the data types are converted.

```
/// 8)  Calculate Floor Area Ratio
foreach (FamilyInstance parcelModel in parcelFamilyInstances)
{
    /// string which will be passed to ModelInfoViewer
    if (parcelModel == null) continue;
    StringBuilder sb = new StringBuilder();
    /// Parameter "Volume" can be obtained from ParameterSet!!!
    ParameterSet lotparameters = parcelModel.Parameters;
    string modelName = parcelModel.Name.ToString();
    string parcelName = modelName.Substring(0, 4);
```

Figure 3. A code block for locating a BIM object set from the parametric urban code model.

```
///Internal variables to calculate F.A.R.
lotArea = parcelModel.get_Parameter("Area").AsDouble();
int parcelArea = (int)lotArea;
lotCode = parcelModel.get_Parameter("Code").AsString();
lotName = parcelModel.get_Parameter("Name").AsString();
string fileName = lotName + lotCode;
```

Figure 4. A code block for collecting variables for the density calculation.

```
foreach (FamilyInstance codeModel in codeFamilyInstances)
{
    ParameterSet parameters = codeModel.Parameters;
    string faNames = codeModel.Name.ToString();
```

Figure 5. A code block for entering a building component.2

```
    if (faNames.Contains(lotName))
    {
        totalFloorArea
        = codeModel.get_Parameter("Gross Floor Area").AsDouble();
        int TFA = (int)totalFloorArea;
        /// Calculate Floor Area Ratio
        floorAreaRatio = totalFloorArea / parcelArea;
        string FAR = floorAreaRatio.ToString().Substring(0, 4);
```

Figure 6. A code block for calculating density using internal variables.

Figure 5 shows an entry point to access a building component. We named the building component as the codeModel. The required parameters are stored in the 'Parameters' class of the codeModel, so we define an internal parameter set with this class.

The area of total building floors can be obtained from the building component parameters. The parameter name value is Gross Floor Area, and the value is stored as a double type. We store the value into the internal variable of TFA as an integer. Using two variables of the parcel area and the total floor area, we can calculate F.A.R. that can measure the development density (Figure 6). The last step is to

store internal variables into a parameter list as a series of strings, which will be presented in the viewer in Figure 2.

4. Conclusions

In this research, we implemented the parametric urban design code model using BIM and OOP. It could visualize key provisions of urban design codes and the structure of code components. The applications of BIM API could facilitate interactive communications among multiple code components, which could assess the information within multiple code components and generate new values using such component information. In addition, associations across code components and their provisions also can be established in BIM objects using customized applications. The findings show the potential of the parametric modelling and API in BIM for the real-time design evaluations and model changes during the urban design process.

Provisions governing quantitative aspects of urban design, such as urban form and capacity can be modelled in our prototype, which do not present qualitative aspects of urban design codes. Further research needs to focus on how our prototype can support such aspects of urban design codes.

References

Barnett, J.: 2011, *City Design: Modernist, Traditional, Green, and Systems Perspectives*, Routledge, Abingdon, UK.

Ben-Joseph, E.: 2009, Commentary: Designing Codes: Trends in Cities, Planning and Development, *Urban Studies*, **46**(12), 2691–2702.

City of Peoria: 2010, "Heart of Peoria Form Districts". Available from: <http://www.ci.peoria.il.us/development-codes> (accessed 9 October 2012).

City of Ventura: 2007, "Downtown Specific Plan". Available from: <http://www.cityofventura.net/downtown> (accessed 10 October 2012).

Cox, B. J.: 1986, *Object-oriented programming; an evolutionary approach*, Addison-Wesley, Reading, MA.

Eastman, C. M., Teicholz, P., Sacks, R. and Liston, K.: 2008, *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors*, John Wiley, Hoboken, NJ.

Hascic, I.: 2006, *Essays on land use regulation*, Oregon State University.

Kim, J. B., Clayton, M. J. and Yan, W.: 2011, Parametric Form-Based Codes: Incorporation of land-use regulations into Building Information Models, *Parametricism (SPC). Presented at the ACADIA Regional 2011 Conference*, Lincoln, Nebraska.

Sacks, R., Eastman, C. M. and Lee, G.: 2004, Parametric 3D modeling in building construction with examples from precast concrete, *Automation in Construction*, **13**(3), 291–312.

Walters, D.: 2007, *Designing Community: Charrettes, Master Plans and Form-Based Codes*, Elsevier/Architectural Press, Amsterdam.

ROBOTIC FABRICATION

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A SOFTWARE ENVIRONMENT FOR DESIGNING THROUGH ROBOTIC FABRICATION

Developing a graphical programming toolkit for the digital design and scaled robotic fabrication of high rises

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Abstract. The term "robot" was born from a play written almost a century ago. Today robotic fabrication has become an emerging topic in architectural research. As architects work with these technologies, they are challenged with writing a different kind of play: here robots are the actors and the physical materialization of a design is their performance. However current Computer Aided Design (CAD) packages do not provide native robot programming functionalities which architects require to plan and orchestrate these fabrication process. To address this limitation, a Python library for robot programming is written. It is referenced by a toolkit of custom components developed to extend a graphical programming environment commonly used for architectural design. The empirical development of these software tools takes place in the context of a design studio investigating the subject of the high rise. The tools are tested in a workflow that involves the digital design and scaled robotic fabrication of high-rise housing. This paper discusses the considerations underlying the toolkit's design, the outcomes of its use in the studio, and its impact on the creative design process.

Keywords. Robotic fabrication; Architectural model; Software tools; High Rise design; Creative computational design.

1. Introduction

In 1920, during a period of widespread optimism in technology, Karel Čapek wrote a play from which the term "robot" was born.[1] The robots in his story were artificial workers created to replace human labour in the serial production of goods. Almost a century later, robotic fabrication has emerged as a topical area of

research in the field of architecture. Here, industrial robots are used for the production of digitally described building components that are often highly individualized.

This process requires the authorship of both design data, usually encapsulated in three-dimensional digital models, and production data, in the form of robot programs describing fabrication steps. However Computer Aided Design (CAD) packages used by architects nowadays only facilitates the digital design process. To plan and control the subsequent fabrication process, separate offline programming software provided by robot manufacturers is often used instead.[2] Thus at the software level, design and production are defined as being distinct tasks.

In order to conceive of design and production as a comprehensive process[3], the lack of robot programming and control functionalities in current CAD packages needs to be addressed. This paper describes the development of a custom Python library called *Your* which provides these functionalities for the Rhinoceros/Grasshopper[4] CAD platform. Using this extended environment, architects are now able to explore designs and plan production processes in a seamless manner. This paper will discuss the use of these new tools in the context of a design studio, as well as their impact on the creative design process.

2. Context of the Robotic Fabricated High Rise

This past decade has witnessed increasing experimentation with robotic fabrication within the architectural field. Thus far such work has concentrated on elements of a building and been limited in size. To meet the challenge of applying robotic fabrication at the large scale, the Chair of Architecture and Digital Fabrication[5] at ETH Zurich set up a research group at the Future Cities Laboratory[6]. The primary topic of investigation is the design of robotic fabricated high rises.

An initial strategy of scaled robotic fabrication is pursued in order to address the high rise building as a comprehensive design subject. Here, physical models are directly fabricated from digital data, and play an important role in the conception and testing of architectural ideas. This approach offers considerable benefits for high rise design. Physical models provide direct and intuitive feedback about structural behaviour. This is significant for high rises as the resolution of both vertical and horizontal loads[7] is an important design task. The principle of additive assembly, which the model building process is based on, applies to 1:1 high rise construction as well.[8] Constructive concepts can thus be developed in the early design process and tested through robotic building.

An architecture studio exploring the subject of contemporary high rises in Singapore forms a key part of the research project. A workflow is adopted that

involves the digital design and scaled robotic fabrication of high rise housing. The model building process is based on the additive assembly of parts through pick and place operations. To facilitate this prototypical design methodology, a set of bespoke software tools called *Your* was developed for use in the studio.

3. Software Development

Your consists of a package of Python modules that adds the following functionalities to the Rhinoceros/Grasshopper CAD platform: a wrapper for the scripting language of the robots used, utility transformation functions, kinematics solvers and computer-robot communication. This package can be referenced through the script editor in Rhinoceros or Python components in Grasshopper; either environment can now be used for authoring robot programs.

For the design studio, Grasshopper was selected as the underlying environment for design and fabrication. This was due to the following considerations: firstly many students did not have prior programming experience and were unfamiliar with algorithmic approaches to design, and secondly the physical fabrication setup was expected to be frequently modified by students over the course of the studio. Here the visual programming and parametric nature of Grasshopper are advantages. Algorithmic logics can be implemented in a visual way by connecting components; this is accessible to non-programmers as it does not require writing code. By assigning fabrication parameters that are adjustable, Grasshopper definitions can be adapted to changing physical setups without the need for restructuring.

Based on this decision, a toolkit of Python scripting components, each referencing *Your*, was further developed for use in Grasshopper (Figure 1). The aims of the toolkit are twofold. First, it has to be easy to use so that robotic building is

Figure 1.

immediately accessible during the early design phase. Second, it has to be adaptable in order to allow experimentation with custom developed robotic processes.

The toolkit components are grouped into: setup, commands (interface, motions and custom actions), robot communications and kinematics. Setup components allow physical information such as the model building base to be stored. Command components wrap default URScript[9] functions; inputs are given in intuitive to understand formats, for example orientation data as planes rather than axis-angles[10], and the output is auto-generated UR scripts. Robot communication components handle the sending and receiving of data through sockets, while kinematics components provide a way to visualize and simulate the robot. These components provide the necessary functionalities for a complete robot program to be created and sent. With tasks such as code generation, socket communications and coordinate system transformations handled behind the scenes, designers can focus on the logical assembly of components to define a program.

Other projects such as KUKA|prc[11] and HAL[12] also provide robot programming functionalities in Grasshopper through custom components. A distinguishing feature of the approach taken here is the emphasis on end-user modification. This was a consideration from the outset as having closed and overly specific components would have inhibited experimentation with bespoke robotic processes. All components provided in the toolkit are therefore open with internal code exposed. They serve as example blueprints, which users refer to when developing their own eventual components.

4. Studio Outcomes

During the design process, students create grasshopper definitions that contain both design and production data. These definitions are structured in four general parts (Figure 2). First, design information is generated and then parsed to get raw input data for command components; this involves the use of regular Grasshopper components. Second, information regarding the physical fabrication setup is added; setup components from the toolkit are used in this step. Third, detailed robot instructions are generated describing action and motion sequences; robot command components from the toolkit are predominantly used here. Finally, instructions are sent to the robot for execution with the help of communication components.

Two projects, which illustrate the main approaches emerging from the studio, are selected for further discussion (Figure 3). They both employ a constructive system involving the assembly of horizontal and vertical parts. However in the first case, each part is unique with shape information added by the laser cutter. In the second case, standard parts are used and subsequent information is added through a robotic deformation process.

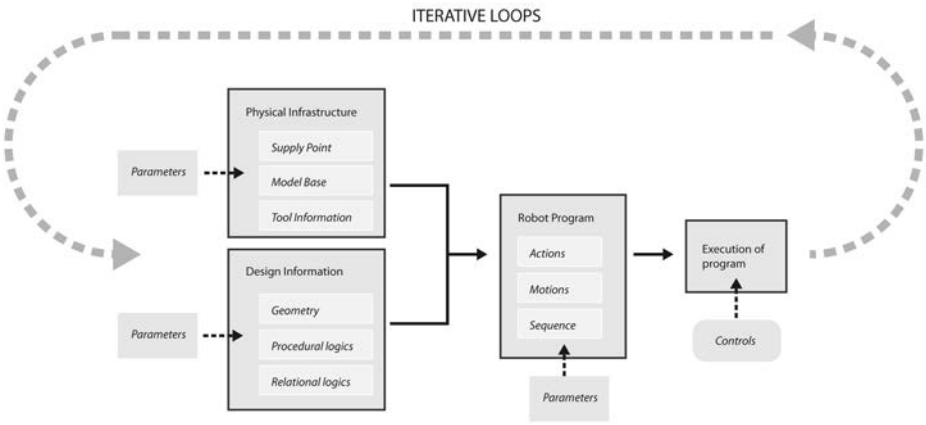

Figure 2.

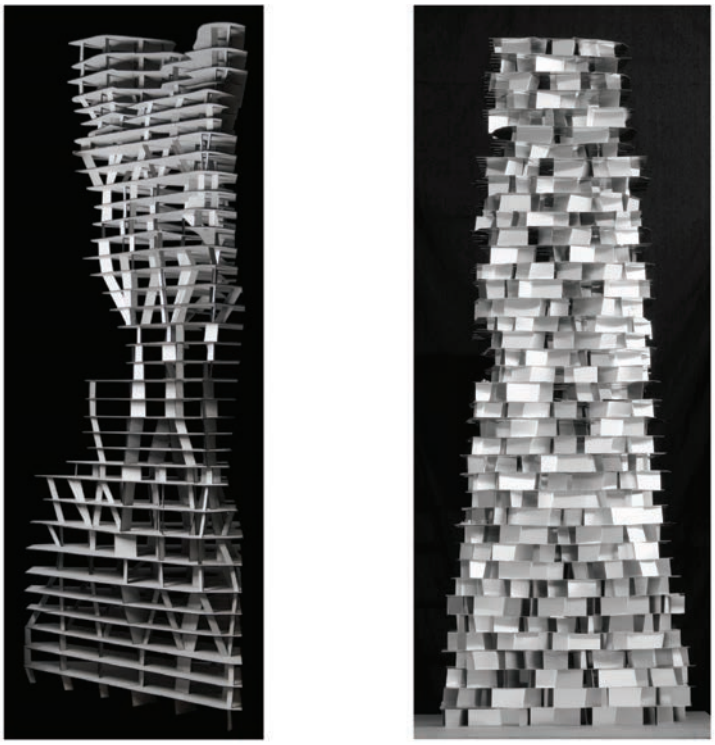

Figure 3.

4.1. DESIGNING WITH MANY UNIQUE PARTS

A main intention of *Team Bahru's*[13] project was to explore the design potentials of a production process that enables every part of a building to be unique. Several tower versions were constructed that were assembled out of laser-cut cardboard walls and slabs.

Design and robot programming were separated in two Grasshopper definitions. In the first, an associative model was developed to explore the design of the high rise. Selected versions were baked[14] in Rhinoceros as three-dimensional geometry. A subsequent Grasshopper definition for robot programming was created that referenced this baked geometry. From this, two-dimensional drawings of walls and floors were generated by a custom developed python scripting component, and organized into cut-sheets for the laser-cutter. Cut-sheets were placed in a physical feeder and provided picking information for the robot. Baked geometry provided raw information for placing operations.

For earlier tower versions, pick and place components from the toolkit were mainly used. However with the shift towards unique parts in later designs, robot motion trajectories had to be planned in greater detail to avoid issues of collision and imprecision. Pick and place components, which encapsulated pre-defined safety motions and actuator actions, were modified by the students. Components that provided lower level functions, such as linear motion, were assembled together to describe more complex building tasks. The eventual program was split into chunks and sent; parts were picked, placed and glued by the robot storey-by-storey. During the fabrication process, parameters such as the height of the model building base or wait times for gluing could be adjusted to account for material tolerances and building inaccuracies.

Two key design ideas of a branching system of twisted shear walls and a continuous central void were studied through a series of models. Tower fragments were built to test the positioning of walls and amount of twist that could be implemented without losing structural integrity. Different void shapes were studied to evaluate the effects on day-lighting and interior views. Based on the feedback gained from these physical models, the digital models were subsequently adjusted and refined, before being materialized again.

4.2. DESIGINING WITH ONE FOLDED PART

The design approach undertaken by *Team Rochor*[15] was to derive maximum complexity from a simple material folding process. This process became a key design driver and determined the formal vocabulary of the high rise. Two 1:50 models were fabricated using a floor and folded-wall constructive system.

The team experimented with several modelling materials including cardboard and aluminium. Rules for folding were established, and the range of forms produced from their different permutations catalogued. Folded walls were produced in this manner; they were positioned based on rules that ensure the direct vertical transfer of loads to the immediate walls below. Design solutions were arrived at that negotiated between the formal possibilities offered by the folding process and the positional constraints imposed by the structural logic. A parametric model was developed to describe this.

The model assembly process was composed of repeated pick, fold and place operations. Cardboard or aluminium rectangular pieces were stacked on a simple feeder; as they were all standardized, one picking action could be programmed and repeated. The parametrically defined high rise design provided the raw information for placing. The main complexity of the robot program came from the folding operation. Students determined the precise robotic motions needed for folding a desired shape and encapsulated the logic in a cluster of basic toolkit components. The robot program was developed in relation to a customized physical setup, which included an actuated clamping station that was used in the folding process. To account for different material stiffness and malleability, additional parameters were added that allowed the speed and amount of over-folding to be adjusted.

In this project, the inherent stability of the folded wall meant that the model could be stacked without glue. The robot program was sent in chunks and after every level was built, the fabrication process was paused. The physical model could be evaluated at this stage and dissatisfactory parts disassembled by hand. Design parameters were tweaked, and this was automatically propagated to the robot program. The script for the previous disassembled level is then replayed. In this manner, the team was able to change the high-rise design during the building cycle itself.

5. Evaluation of Toolkit

The toolkit was empirically developed and tested over the course of the studio. Based on student feedback and direct observation of its use, the toolkit was iteratively refined to address identified bugs and missing functionalities. While the original toolkit given out contained six components, this number expanded to twenty by the end of the studio.

The first aim of the toolkit was to be easy to use so that robot programming would be accessible. In a three day workshop conducted at the start of the studio, students were introduced to toolkit for the first time and were able to successfully program the robotic fabrication of models up to a meter tall by its conclusion. In

interviews conducted at the end of the studio, students gave positive feedback when asked to evaluate the effectiveness of the toolkit in easing robot programming. The following responses were offered: the plug and play approach was considered to be intuitive to understand and accessible as it required no prior programming knowledge; the visual representation of robot programs as connected graphs rendered their structure and sequence more legible and were thus easier to edit; the auto-generation of robot scripts through components was a positive feature as it guaranteed code that was error free and executable by the robot.

A second objective was to enable architects to develop bespoke fabrication processes to design with. In this regard, the openness and extensibility of the toolkit enabled students to explore a range of robotic processes without being unduly constrained. This took place in three ways and usually in accordance with the development of a physical setup. The first approach involved assembling basic motion and action components to define more complex sequences. Second, students adapted pre-existing toolkit components by selectively editing and adding lines of code within it. Finally, custom scripts that reference *Your* library were written from scratch within Python components. In one example, a component was developed for a process involving plastic strip bending with a hot air gun.[16] As projects evolved to incorporate custom fabrication processes, students began to actively modify the toolkit and the development of such components became commonplace.

6. Conclusion

The versatility of general purpose industrial robots has enabled them to be adapted for use in architectural design. This versatility is derived in large part from their programmable nature. This paper makes a case for robot programming interfaces to be directly embedded in the Computer Aided Design environments used by architects. Through the example of *Your* toolkit, it is suggested that graphical programming based interfaces offer benefits in terms of ease of use and adaptability.

By extending CAD environments in this direction, digital design and physical production can be merged from the outset. The planning of robotic production processes takes place concurrently with design exploration and the two become mutually informing. The production process enables the creation of physical models that are reproducible, easily varied and serial. Architectural ideas explored in the digital medium can now be directly evaluated in the added physical dimension through iterative model-building. At the same time physical production processes impose formal and organizational constraints that help define the space of design possibilities. In this mode of working, an architect is no longer just a form-giver, but takes on an expanded role as designer and orchestrator of production processes for realizing form.

Endnotes

1. The play “Rossums Universal Robots” was a cautionary story about a servile force of robot workers that eventually revolted against their human creators.
2. In offline programming a user directly creates a robot program and determines its structure, flow and content – this is usually done through a computer. An example of such software is RobotStudio by ABB.
3. (Willman et al., 2012, p. 13).
4. Rhinoceros is a 3D modelling software by McNeel. Grasshopper is a graphical algorithm editor for Rhinoceros. See: Rhinoceros NURBS Modeling for Windows. http://www.rhino3d.com/developer.htm (25.6.2012). See: Grasshopper – Generative Modelling For Rhino. http://www.grasshopper3d.com/ (28.6.2012).
5. See: Gramazio & Kohler Architecture and Digital Fabrication – ETH Zurich. http://www.dfab.arch.ethz.ch/web/e/about/index.html (20.6.2012).
6. The *Future Cities Laboratory* (FCL) is a trans-disciplinary research centre focused on urban sustainability in a global frame. See: Future Cities Laboratory. http://www.futurecities.ethz.ch/ (20.6.2012).
7. A characteristic of a high rise is that it faces significant horizontal loads, in addition to vertical ones (Grohmann and Kloft, 2012, p. 77).
8. In the case of Singapore, the predominant method of high rise construction is the assembly of pre-fabricated reinforced concrete panels.
9. URScript is the proprietary scripting language for the Universal Robots used.
10. Orientation information is generally represented in one of the following formats: matrix, axis-angle notation and quartenions.
11. KUKA Parametric Robot Control (PRC) is a plugin for Grasshopper for programming KUKA robots (Brell-Cokcan and Braumann, 2010).
12. HAL is a plugin for Grasshopper for programming ABB robots (Schwartz, 2012).
13. This was a student project by Florence Thonney, Pascal Genhart, Patrick Goldener, and Tobias Wullschleger.
14. Baking is the operation of adding geometrical objects, created in Grasshopper, to a Rhinoceros documents. The object’s associative relationships are severed.
15. This was a student project by Martin Tessarz, Sebastian Ernst, Silvan Strohbach and Sven Rickhoff.
16. This was a student project by Sylvius Kramer and Michael Stünzi.

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References

Biggs, G. and MacDonald, B.: 2003, A Survey of Robot Programming Systems, *Proceedings of the Australasian Conference on Robotics and Automation*, Brisbane.

Bonwetsch, T., Kobel D., Gramazio, F. and Kohler, M.: 2006, The Informed Wall: Applying additive digital fabrication techniques on architecture, *ACADIA 2006: Synthetic Landscapes. Proceedings of the 25th Annual Conference for the Association for Computer-Aided Design in Architecture*, Lousiville, 489–495.

Bonwetsch, T., Bärtschi R. and Helmreich M.: 2012, BrickDesign: A software for planning robotically controlled and non-standard brick assemblies, *in* Brell-Cokcan S. and Braumann J. (eds.), *Robotic Fabrication in Architecture, Art and Design*, Springer, Vienna, 102–109.

Brell-Cokcan, S. and Braumann, J.: 2010, A New Parametric Design Tool for Robot Milling, *ACADIA 10: LIFE in:formation, On Responsive Information and Variations in Architecture*, New York, 357–363.

Čapek, K., translated by Jones, C. N.: 2004, *Rossum's Universal Robots*, Penguin Books, New York.

Gramazio, F.; Kohler, M., and Oesterle, S.: 2010, Encoding Material, *Architectural Design*, **80**(4), 108–115.

Gramazio, F. and Kohler, M.: 2008, *Digital Materiality in Architecture*, Lars Müller, Baden.

Grohmann, M. and Kloft, H.: 2002, Load-bearing Structures, *in* Eisele, J. and Kloft, E. (eds.), *High-Rise Manual: Typology and Design, Construction and Technology*, Birkhauser, Basel, 76–95.

Menges, A. and Ahlquist, S.: 2011, *Computational Design Thinking*, John Wiley, West Sussex.

Menges, A. and Schwinn T.: 2012, Manufacturing Reciprocities, *Architectural Design*, **82**(2), 118–125.

Schwartz, T.: 2012, HAL: Extension of a visual programming language to support teaching and research on robotics applied to construction, *in* Brell-Cokcan S. and Braumann J. (eds.), *Robotic Fabrication in Architecture, Art and Design*, Springer, Vienna, 92–101.

Willman,, J., Gramazio, F., Kohler, M. and Langenberg, S.: 2012, Digital by Material: Envisioning an extended performative materiality in the digital age of architecture, *in* Brell-Cokcan S. and Braumann J. (eds.), *Robotic Fabrication in Architecture, Art and Design*, Springer, Vienna, 12–27.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 55–64. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

FISAC VARIATIONS: AN INTEGRATED DESIGN AND FABRICATION STRATEGY FOR ADAPTABLE BUILDING SYSTEMS

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Abstract. The promise of robotic fabrication as an enabler for mass-customization in Architecture has been hindered by the intricate workflow required to go from parametric modelling to CNC fabrication. The lack of integration between highly-specialized proprietary software, normally required to operate the machines, and most of the design tools constitutes a major limitation. One way to tackle this constraint is by developing simple tools that directly link parametric modelling to robotic coding. Accordingly, "Fisac Variations" develops an uninterrupted digital workflow from form-generation to robotic fabrication. This innovative approach to Computer Aided Design and Manufacturing was tested by studying and reengineering a specific historic construction system – Miguel Fisac's Bones System was used as a case study – and by enabling it to address problems of contemporary architectural agenda such as flexibility, variability and mass-customization. The proposed workflow threads form-finding, structural analysis, geometric definition, CNC code generation and digital fabrication within the same open-source computational environment. In this way, this innovative procedure aims to increase design freedom while ensuring fabrication feasibility. This paper describes background research, concept, form-finding, construction process, methodology, results and conclusions.

Keywords. Parametric design; digital fabrication and construction; integrated design and fabrication; mass-customization; Miguel Fisac Bones System.

1. Introduction: Integrated Robotic Fabrication

In contrast with highly task-specific CNC machines, robots are versatile equipment that can be adapted to perform a myriad of tasks, including milling, assembling, cutting, welding, and painting among others. In the realm of architecture, the potentials of such versatility seem to align well with current efforts to materialize

complex projects. Although numerous explorations on the robotic fabrication for architecture taking place around the world suggest promise, applications are still under development (Picon, 2010).

In many industrial settings, particularly in the automobile industry, robots have proved extremely successful for the past few decades. On the contrary, their applications in the construction industry have been slow and uneven. One of the key differences is that car manufacturing is highly repetitive and therefore robots are very finely calibrated to repeat very specific routines; calibration tasks pay back due to the high volume of production. In contrast, the construction industry requires highly customized components, especially for buildings of complex geometry, requiring a large number of specific robotic instructions. Additionally, the creation of robotic code is intricate because bringing geometric information from modelling software into the proprietary software, required to operate the machines, becomes a time-consuming and tedious operation (Bechthold, 2010).

As a response, some initiatives are starting to develop simple tools that link parametric modelling to robotic coding. This approach has been explored for robotic CNC milling by Brell-Cokcan and Braumann (Brell-Cokcan and Braumann, 2010; 2011). Project HAL, by Thibault Schwartz, develops robotic code for ABB robots directly from parametric modelling tools – McNeel Rhino/Grasshopper (Schwartz, 2009).

2. Fisac Variations

"Fisac Variations" researches the potential of directly linking parametric modelling with robotic fabrication, with the aim of engaging current architectural concerns such as complexity, variation and differentiation. The two main objectives are: developing custom code that allows for an uninterrupted digital workflow from form-generation to robotic fabrication, and testing this workflow by re-envisioning a prominent – yet rigid – construction system in contemporary key.

The digital workflow proposed by "Fisac Variations" combines form-generation, structural analysis, geometric definition, CNC code generation and robotic fabrication within the same open-source computational environment. In this way, this integrated procedure aims to increase design freedom while ensuring fabrication feasibility and stimulating design innovation.

2.1. MIGUEL FISAC'S BONES SYSTEM

As a case study, the project revisits the "Huesos Varios" (Spanish for Various Bones), developed by the eminent Spanish architect Miguel Fisac during the 60s as an elegant and efficient structural system for long span roofs (González Blanco, 2007).

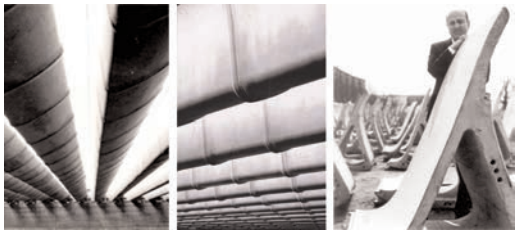

Figure 1. Images of Fisac Bones System.

> "The pieces that I have obtained using this architectonic-static means have resulted in sections with forms very like the bones of vertebrates. It is not that I wanted to make them like bones; it is just that they turned out that way. That makes you think that, naturally, some parallel exists. You could interpret it as proof that this is the right path; it corresponds to concepts which we see in nature." (Fisac, 1966).

The "Bones" system consists of a string of identical concrete voussoirs that are post-tensioned to assemble long beams (Figure 1). The key point of this system is a smart and meticulous design of the cross-section, which solves several structural and construction problems: the pieces are hollow, making them lighter while keeping a high moment of inertia; the asymmetric geometry creates openings for natural lighting; the valley collects and drains the rainwater; and the curved geometry improves the acoustic performance of interior spaces. The post-tension action improves the waterproofing of concrete as it reduces the risk of cracks (Figure 2).

The major limitation of Fisac's system lies in its inflexibility. First, the system works almost only for linear arrays of beams for flat and orthogonal slabs, which limits the building typologies that could potentially adopt this structural system. One experiment with radial array presented unresolved technical issues in relation to the joints and it was not very successful in aesthetic terms (Tejada House, Madrid, 1967). Additionally, the light wells created by the system are locked into a single pattern, homogenizing the natural light distribution and making the system difficult to accommodate different programmatic functions.

2.2. VARIATIONS

Using advanced digital tools, "Fisac Variations" expands the structural efficiency, natural light control and water draining logic of Miguel Fisac "Bones" to reach new levels of tectonic and formal complexity. The main goal is to develop a mass-customizable system that can deal with wider and more complex range of structural, programmatic and organizational requirements.

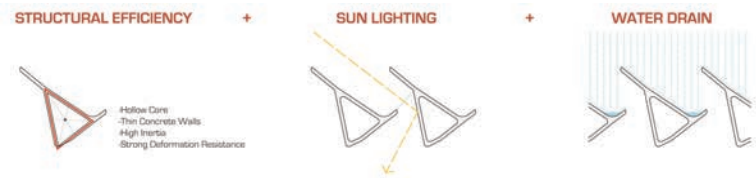

Figure 2. Bones system salient features.

The result is a flexible construction system open to accommodate diverse programmatic functions. Moreover, the structural performance of the new typologies exceeds the beam logic and proved more efficient as they can follow natural stress lines, minimizing the bending stresses and allocating material specifically where needed.

3. Implementation

In order to attain flexibility while achieving a feasible construction method, the project integrates manufacturing constraints and robotic control into a single smart parametric model. “Fisac Variations” develops an innovative fabrication workflow for architecture by customizing open-source software for robotic fabrication. The code is based on McNeel Rhino/Grasshopper, Microsoft C# and ABB Rapid Code.

3.1. DIGITAL DESIGN: SYSTEM GENEALOGY

Fisac Variations is designed to adapt to a wide-variety of surface geometries, from flat to non-zero Gaussian curvature. The form-generation and geometrical development process takes advantage of an associative model that encodes the clever cross-sectional features of the original system into a six control points’ section (Figure 3). These variable sections can change along the span of the beams and each pair of them defines a voussoir through a loft operation. Thus, this process allows for gradual variation between pieces and specific control of its performance, being able to modulate the geometry in response to particular structural, spatial and lighting requirements.

Another innovation that the project introduces to the original system is the concept of ‘girder’, a technical improvement which enables the connection between pieces in two directions. This feature eliminates the need for continuous linear supports in the extremes – present in Fisac’s system.

The code defines a collection of beams, organized according to a quadrilateral input surface called ‘quad’. To generate the geometry, the Grasshopper definition can take two different pieces of data: a custom quadrilateral surface or four vertex points. If a custom quad surface is used as an input, the given surface is discretized

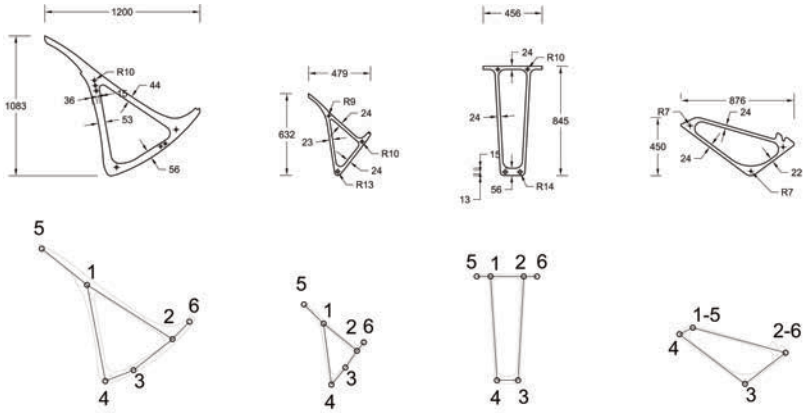

Figure 3. Parametrization of the Bones Series using six control points.

into a number of segments and corresponding fabrication curves. Alternatively, if four vertex points are used as input, an additional step allows the user to specify the geometry of the edge curves.

The script also provides detailed control of the depth and thickness of the sections, as well as the ability of determining the location and size of openings and draining channels. Structural constraints are coded to define geometric thresholds, such as the curvature that beams and girders can describe in plan. For example, in order to the voussoirs be post-tensioned, the deviation should not exceed 10% of the span.

The girders located on the edges of the quad confer the latter with the capacity to work associated with others and, therefore, to proliferate into more complex spatial and programmatic organizations (Section 6.1).

As a design output, the code creates a set of unique pieces adapted to their specific needs. The script also generates the connection between the voussoirs: a set of interlocking keys that facilitates the assembly and improves the structural performance.

3.2. ROBOTIC FABRICATION

Robotic fabrication can be applied to several tasks, including mould-making, concrete casting and vibrating, as well as voussoirs unmoulding and handling. Due to the limited scope of this research, the focus was placed on the first step of the process, mould-making, and on the development of coding that converts the geometry into robotic instructions using ABB Rapid Code. The operation sequence for cutting each piece is automatically named and stored into individualized files that feed the 6-axis robotic arm (Figure 4).

Figure 4. Robotic Cutting Sequence.

Figure 5. Wire Cutting Tool.

For each one-off voussoir, a customized mould is fabricated by cutting recyclable expanded polystyrene (EPS – 20kg/m3) with a hot-wire bow attached to a robotic arm. This custom tool uses standard components and a commercial AC power controller (Figure 5). As a logical limitation from this procedure, all pieces are defined by ruled surfaces.

This mould-making technique is fast, precise, affordable and easily recyclable. The tool can be adjusted depending on the desired size of the piece to be cut; yet, the cutting speed needs to be calibrated according to the length of the wire. A complete cutting sequence of a full-scaled beam module takes approximately 15 minutes while a girder module takes 25 minutes, for pieces one-meter long.

4. Tectonics: Concrete Casting and Off-Site/On-Site Assembly

The EPS moulds are then casted with concrete to produce the highly-customized voussoirs. During the 60's, when Miguel Fisac developed his 'Bones', the minimum thickness and the maximum size of the voussoirs was limited by the concrete performance and the vibration techniques available at the time. Today, high-tension and self-compacting concrete mixtures combined with efficient assembly lines facilitate the process and open a new spectrum of sizes and thicknesses. Also, departing from the original system, the pieces are not hollow: after the casting, the core is left to fill the cavity as an insulation improvement, taking advantage of the EPS thermal properties (Figure 6).

Figure 6. Full-scale voussoirs –wirecutted EPS (left) and casted concrete (right).

Regarding the assembly sequence, first all the voussoirs corresponding to a beam are interlocked on the ground using the EPS mould as a support. Secondly, they are post-tensioned to assemble each beam individually. This process can be done either off-site or on-site. Finally, after putting all the beams in their final position – with or without the use of scaffolding depending on the support condition-, the girders are post-tensioned in the opposite direction, perpendicular to the beams connection.

5. System Performance

The resulting system introduces variability in both the overall and the module geometry. As a result, "Fisac Variation" is able to adapt to a wide range of span-lengths and structural typologies, from flat slabs to compression-only structures and to free-form surfaces. This condition provides the project with a new expressive quality and flexibility to adapt to topological variation and functional complexity. Accordingly, the movement of the six points that determine the encoded cross-section produces differentiated beams, allowing customization of the interior space morphology as well as fine-tuned control over acoustics, water drainage and natural lighting (Figure 7).

The sound performance can be enhanced by smoothing the beam surfaces, reducing the noise reflection within the building. Regarding the rain water, it can be canalized into desired drainage paths through the subtle movement of the lips that form the upper surface of the pieces. The same feature also permits to adjust the light entrance, admitting gradual or abrupt variations, in harmony with spaces use and distribution.

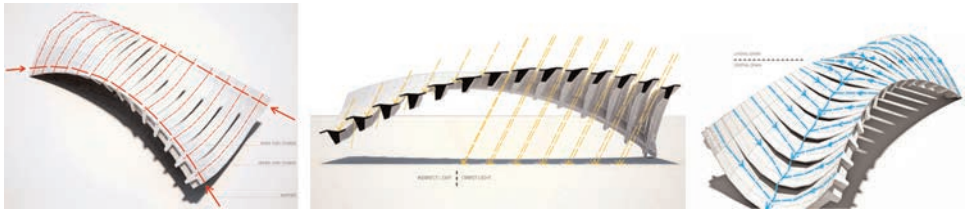

Figure 7. Structural performance (left), direct and indirect natural lighting (centre) and water drainage strategies (right).

6. Design Speculations

6.1. PROLIFERATION

Fisac Variations, as building system, can achieve complex organizations through the proliferation of quads into larger fields. This property incorporates new layers of sophistication to the research project and expands its range of application by the capacity of allocating contemporary mixed-use programs into complex spatial configurations (Figure 8).

6.2. SCALES OF APPLICATION

Because of the discretization principle under which the geometry is conceived, explained in detail in Section 3.1, the same quad can be subdivided into different number of voussoir. By augmenting their quantity, the geometrical resolution gets higher, enhancing a detailed control over the system performance described in Section 5. Nonetheless, the pieces become smaller, increasing fabrication and assembly complexity. As a consequence, the final number of modules is a negotiation between these two factors. In a speculative perspective, possible applications of the proposed system can range from domestic to infrastructural applications (Figure 9).

7. Prototypes

Several building prototypes and consultancy with engineers showed initial feasibility for “Fisac Variations” as an efficient customizable structural system and

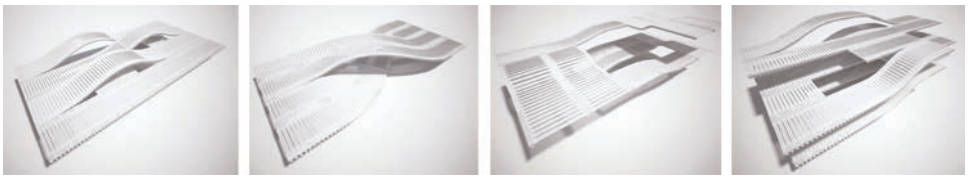

Figure 8. Quad proliferation.

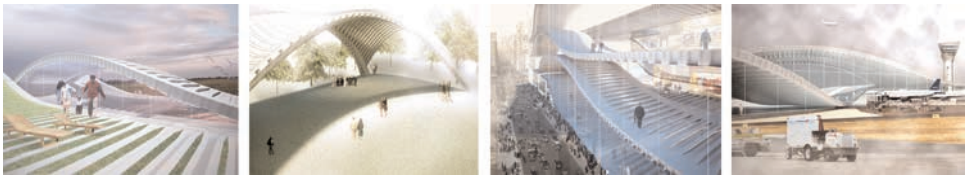

Figure 9. Design Speculations at different scales: domestic, pavilion, commercial, airport.

Figure 10. 1:5 prototype in EPS.

established accurate thresholds for spans and geometrical variation. As a proof of concept, a 1:5 large-scale structure in EPS was built, satisfactorily testing geometric accuracy and post-tension feasibility, as well as aesthetic and spatial effects (Figure 10). A full-scale mould was cast and proved operative.

8. Future Research

Several areas of research deserve further development in order to make the proposed workflow and building system fully operational. First, integrating a structural analysis component is essential for tectonic reasons and will also enrich the design process. Second, increasing the scale of fabrication will require additional research on larger robotic shops and customized CNC wire machines. This feature would allow exploring new ranges of robotic fabrication as described in Section 3.2. Finally, on-site assembly sequence, which includes transportation, placement and scaffolding, is on its initial stages of developments and demands careful study.

9. Conclusions

“Fisac Variations” researches the potential of robotic fabrication and integrated design-to-fabrication workflows as a means to enable complex geometric and tectonic assemblies, which rely on mass-customized components. Results presented in this paper show how customized scripts can embed fabrication constraints to parametric modelling and thus simplify the complicated workflow that currently limits robotic construction in Architecture.

As a specific project, “Fisac Variations” proposes a new efficient, adaptable and feasible structural system, attainable only through integrated use of digital design and fabrication. The result expands the range of possible uses of the original Bones System and helps to overcome some of the formal and structural limitations that caused its obsolescence. As with the case of Miguel Fisac’s designs, the formal and expressive qualities of the resulting models and prototypes reveal that the system can drive structural efficiency into sophisticated architectural spaces.

Instrumentally, the highly customizable set of tools and workflows developed through this project complements on-going robotic coding research and is open to be applied over different tectonic systems (Brell-Cokcan and Braumann, 2010). On a broader outlook, this investigation contributes to current efforts of Computer Aided Design and Manufacturing to realize complex one-off projects.

Endnotes

1. Several projects of EPS cutting with a hot-wire cutter bow attached to a robotic arm have been develop during the last few years at the University of Michigan Taubman College of Architecture and Urban Planning Digital FABLab, directed by Wesley McGee.
2. Changing the length of the bow also modifies the length of the hot-wire; therefore, the cable resistance is different in each case, affecting the amount of power needed to cut the EPS. In any case, the speed needs to be calibrated to avoid geometrical imprecisions while cutting the mould: if the speed is set up too fast, it would drag the wire; if the wire runs too slow, it would melt the foam excessively.
3. While off-site assembly offers better performance according to building time execution, on-site assembly overcomes the existence of transportation constraints, typical of crowded urban centres–sometimes with narrow streets-, by moving the voussoirs to the site one by one.

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This paper presents the results of a project for the course SCI 0642300 (Re)fabricating Tectonic Prototypes, taught by Leyre Asensio-Villoria at the Graduate School of Design, Harvard University. Her input and advice were pivotal for the development of this research. The positive feedback of Hanif Kara, from London-based firm Adams-Kara-Taylor, as structural consultant was also encouraging and helpful for the development of the system. For machine coding, Panagiotis Michalatos' support was of crucial importance. Last but not least, the support of the Design Robotics Group (DRG) was vital in order to build the robotic tool.

References

Bechthold, M.: 2010, The Return of the Future – A Second Go at Robotic Construction, *Architectural Design*, **80**(4), 116–121.

Braumann, J. and Brell-Cokcan, S.: 2011, Parametric robot control, *Proceedings of the Annual Conference of the Association for Computer Aided Design in Architecture*, ACADIA 2011, Calgary/Banff, 244–251.

Brell-Cokcan, S. and Braumann, J.: 2010, A New Parametric Design Tool for Robot Milling, *Proceedings of the Annual Conference of the Association for Computer Aided Design in Architecture*, ACADIA 2010, New York, 357–363.

Fisac, M.: 1966, *Hormigón y Acero Magazine nº 79*, Asociación Técnica Española del Pretensado, [y] Instituto Eduardo Torroja, Madrid, 36–39.

González Blanco, F.: 2007, *Miguel Fisac: Huesos Varios*. Fundación COAM, Madrid.

Picon, A.: 2010, *Digital Culture in Architecture: An Introduction for the Design Professions*, Birkhauser, Basel.

Schwartz, T.: 2009, "HAL robot programming and control". Available from: <http://hal.thibaultschwartz.com/> (accessed 17 March 2013).

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 65–74. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

ADAPTIVE GROWTH USING ROBOTIC FABRICATION

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Abstract. This paper studies computational methods for adaptive growth seen in human design processes, such as development of spontaneous settlements, by highlighting the contrast with conventional plan execution approaches. The paper speculates as to the possibilities of open frameworks for design using computational methods through a relatively simple yet explicit example in the context of robotic fabrication. The proposed experiment uses an industrial robot arm to produce structures by stacking unit bricks without hard-coded instructions ("blueprints") from the outset. The paper further speculates about how such implementations can be applied to architectural design.

Keywords. Generative design; robotic fabrication; adaptable design.

1. Plan Execution and Adaptive Growth

The development of cities exhibits a remarkable diversity in human creative processes. Paris, New York, Tokyo, or favelas in Rio de Janeiro, all represent different planning strategies and growth processes. According to Alexander (1965), cities that have been deliberately created by planners are called artificial cities, and cities that have arisen spontaneously over many years are called natural cities. Alexander clearly separates them as products of different processes. The former is a plan-execution-based process that delineates all tasks in advance, sequencing them one by one based on a predefined blueprint, whereas the latter possesses a dynamic mechanism that allows it to spontaneously grow and adapt without a complete set of predefined instructions.

Computational interpretations of such systems have been provided by scholars as a form of simulation, and there are reliable software applications that can simulate plan-execution-based systems. There are software applications that can generate hypothetical virtual cities that belong to the category of artificial cities using methods such as shape grammar and L-systems (Müller and Parish, 2001). However, these applications generally cannot be effectively used to simulate the development of cities that possess the characteristics of natural cities. These

design systems require imposing a specific design template based on typological layouts of cities. Oftentimes urban configurations developed by spontaneous settlements are not the results of impositions of specific urban forms and are hard to represent by a collage of discretized typologies. Thus, simulation of informal and spontaneous settlements over long periods of time might be a challenge.

This discussion indicates that the latter type of human design processes requires a different type of computational methods to describe the processes. This paper speculates about the possible computational models for processes which demonstrate growth and adaptation without a predefined blueprint. Providing a comprehensive interpretation for a city's growth is a complex task. Instead, the paper speculates, through simple examples, as to the possibilities of open frameworks for design using computational methods.

2. Growth and Adaptation Method

A computational method for 'growth and adaptation' needs to have a description of gradual growth processes over time. Firstly, a model and its environment for growth have a reciprocal relationship. A model is first created by conditions and constraints inherent in its environment. Then the model's behaviors and growth influence the environment and start to change it. This change in the environment becomes a new incentive for the model to update itself to conform to its new environment. This perpetual feedback between the model and the environment is a continuous loop in time series. This process can be implemented as a computational model by providing an algorithmic description for the model to update its state.

In principle, if we can write a general procedure for a model at arbitrary time T to renew its state at time T+Δt, this model can continue, by updating its state, to grow. This procedure for updating needs to be conditionally applied, based on the states of the environment, which implies that the description of 'self' is not adequate for the description of the model in this category. Such a model needs to be equipped with perceptions of environmental conditions in order to produce its next action. These sensing and action functions are the essential behavior for the model inside the spatiotemporal settings. I list the following examples of this type in order of level of application.

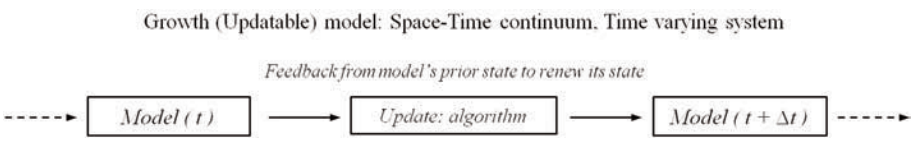

Figure 1. Growth (Updatable) model: Space-Time continuum, Time varying system.

2.1. CONVENTIONAL RENOVATION SCENARIOS

Renovation and addition to existing structures are the most common scenario of application in architecture. These transformations are not planned at the time of the initial construction and are triggered by unanticipated changes in environments, occupancy, and population density in later periods. These alterations are executed at a discrete time step, and there is no continuity between successive transformations. The end of the production is the completion of the product. The production is based on a precisely planned blueprint which includes all possible requirements up to a certain future stage. Discontinuity in growth patterns and the lack of bidirectional spontaneous feedback between buildings and environments characterize this class.

Figure 2. Transformations of buildings over time from How Buildings Learn (Brand, 1994).

2.2. MODULAR SYSTEM (KIT-OF-PARTS)

This example aims at designing a system that can be upgraded for future extensions from the beginning of the planning. This is a characteristic seen in modular systems in architecture. All the future transformations, reconfigurations, and replacements are planned at the initial stage of the construction; however, these changes are pre-defined or constrained by the system's own physical limitations. Metabolists' buildings' infrastructures allowed some reconfiguration patterns of units, yet the growth was limited within the extent of the system's own capabilities. In general, modular systems consist of modular building blocks and infrastructural arteries that can support and combine them. These subunits do not possess active behavior and sensing capabilities able to achieve un-programmed or unplanned configurations.

2.3. SELF-ORGANIZING GROWTH

This is a more advanced application of the growth logic. The subunit is designed flexibly and universally enough so that aggregations of the subunits can adapt to many unpredictable scenarios. In order to achieve this level of flexibility in global structure, the subunits need to have some means of active mobility by having actuation devices within themselves or by relying on other devices for transportation. Collective construction by termites is one extreme example of such structures that do not require any pre-defined configurations. We do not know the exact logic behind them, but the

models by Theraulaz and Bonabeau (1995) show that similar constructions can be obtained from mere locally embedded rules. Procedural instructions alone can continue the construction processes. Swarm robots or reconfigurable robots created by computer scientist groups also belong to this category because they have distributedly controlled subunits with sensing and actuation capabilities (Zykov et al., 2000).

3. Collective Construction

In contrast to construction processes by humans, the Collective Constructions accomplished by termites do not rely on any innate concept or predetermined blueprint throughout their constructions. Camazine et al. (2002) speculate that their building behaviours are genetically programmed responsive acts which are triggered by their surroundings. This kind of stimulus-response is often called Stigmagy (Grasse 1959): information from the local environment under dynamic progressions stimulates and guides further activities in construction. A certain local state of the system becomes an incentive for the next construction for individual workers, and this process continues to feed new information to the builders. In this way, information is always provided from the dynamically changing environment rather than any source of information external to the ongoing construction activities. This is one of the reasons why social insects, such as termites, can undertake complex constructions without knowledge of the ultimate form of the structures. Thus Stigmagy often refers to the information collected from works in progress.

4. Experiments using Robotic Fabrication

In architecture, robotic devices have successfully and faithfully produced constructive forms based on hard-coded instructions by humans and have demonstrated precisions and repetitions that can exceed human capabilities. Unit-based (brick) stacking projects by researchers have clearly demonstrated these advantages of robotic fabrication. Gramazio and Kohler at ETH Zurich (2011) and Design Robotics Group at Harvard have actively used industrial robotic arms for their design experiments since 2005. This section introduces an example of a computational model inspired by collective construction through experiments by the author in the context of robotic fabrication.

4.1. PLAN EXECUTION METHOD

A small industrial robotic arm with a gripper, the IRB-140 by ABB Co. Ltd., was used for the following experiments. The robot is programmable using a C-based language called RAPID, and targets and orientations of the gripper arm are defined based on coordinate numbers and quaternion-based rotation matrices. The author had full access to the robot during experiments.

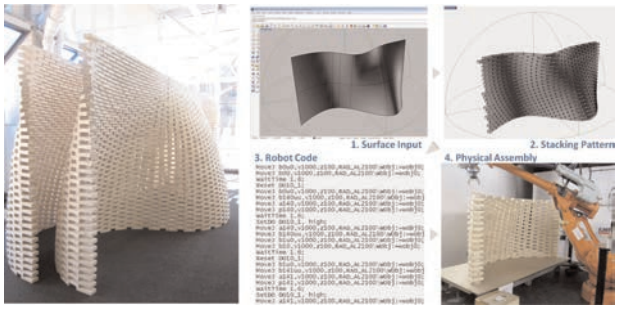

Figure 3. Collaborative application example (left), Tool's process (right).

Firstly, the author wrote a simple middleware program that allows anyone to produce and replicate design geometries in a digital environment to physical forms by connecting the robot with common CAD software, Rhinoceros. It was written in Java and Rhinoscript and was used by several designers for the production of formal variations based on their blueprints (Figure 3, left). The program can interpret any surface geometry as a user-input and can produce a stacking pattern based on a user-defined global geometry relative to a selected size of a modular brick. The program can autogenerate a RAPID code that instructs the robot where and in which order to move and stack the bricks based on the pattern obtained from the original user-defined geometry. The robot executes the code to replicate the original digital form approximated by the size of the unit brick by stacking them in real life. The program can check the stackability of bricks to avoid any invalid placement in terms of physical balance. A series of hard-coded moves and gripper instructions ensures a replication of a predefined form. This is a typical plan execution system's scenario, where all the objectives and tasks are clearly defined in advance, sequenced one by one.

However, there are other design strategies by humans that do not rely entirely on a fixed blueprint. As we discussed earlier, a collective design of spontaneous settlements is one such example. The next section introduces the possibility to actively incorporate the adaptive growth method for the robot's production rule. It is speculated that the machine can, in principle, anticipate and adapt to shifting demands of its human co-workers.

4.2. ADAPTIVE GROWTH METHOD

Using programming in Java and RAPID, the author explored an application possibility to obtain a more flexible and open-ended way to send instructions to the manipulator. In principle, a set of instructions can include target positions as variables which can be defined dynamically and differently each time based on a stochastic process. The project uses a simple yet explicit model that does not rely

on a blueprint from the outset. The program can return structures that satisfy a certain characteristic while maintaining some level of morphological variations using a stochastic selection process.

Firstly, the program needs a buildable footprint area for a structure as an initial input and will not place bricks outside of the area at the ground level. The program finds allowable areas that the next brick can be placed by checking collisions against existing bricks and clearance between a robot's gripper and existing bricks. Subsequently, the program randomly selects a new location to place a brick from the allowable area and calculate a physical balance of the entire structure. Until the program finds a valid stackable position in terms of a physical balance, it will randomly select a new location and repeat the test. This brute force search can continue until there is no more allowable location to place a new brick, and eventually produces a tower structure based merely on a simple rule of physics. Every result of the program differs due to the stochastic nature of the program. However, all results satisfy the same initial footprint condition defined by a user and the premise that the robotic arm can build a well-balanced structure by stacking unit bricks. This operation can be done without hard-coded target positions of all bricks from the outset of the process. The system can find its next position as it proceeds without having a fixed blueprint or providing a specific position in every step.

To attain faster computation speed, the program eliminates all trivial invalid positions before running a calculation based on rigid-body dynamics. Simply checking the location of the centre of mass of the structure at every step relative to outer bricks that are supporting the structure at levels below can eliminate invalid placements based on a test of geometric loading conditions (Figure 4, top). By testing this recursively from the top to the bottom of the structure, the test can eliminate invalid

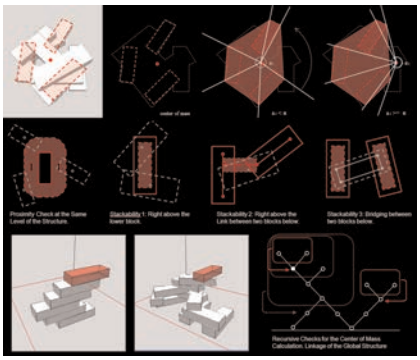

Figure 4. Simplified balance check using centre of mass locations (top) and other steps.

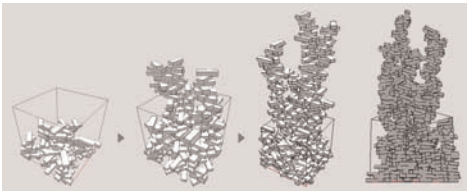

Figure 5. Program written in Java shows the process of adaptive growth sequences.

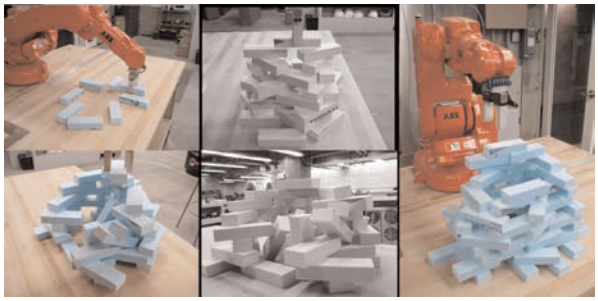

Figure 6. Stacking process without predefined instructions by industrial arm robot, IRB-140.

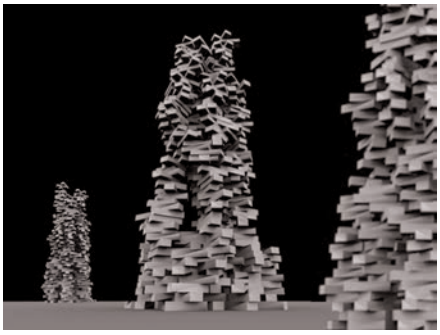

Figure 7. Several instances of resulting structures using the adaptive growth method.

conditions such as an excessive cantilever without a calculation based on moments. Although a configuration of bricks was provided before the construction by the robot, in a future exploration, the faster calculation time will be beneficial for the processing of information based on real-time feedback from devices such as a vision sensor.

Figure 7 shows several instances of resulting structures. Although the rules for stacking are simple, structures often regain integrity by establishing new bridging conditions over the course of constructions. The accidental branching caused by the stochastic nature of the experiment adds morphological diversity for resulting structures, though they are not always the products of pragmatic efficiencies. A literal formal resemblance to the aforementioned nest structure by termites is an intriguing result from the program, though this discussion has nevertheless no scientific validity. The interrelationship between a size and the geometry of the initial footprint area and a relative size and a specific gravity of a unit brick has an important role for deciding the formal characteristics of the structures in these experiments, and this relationship needs to be investigated more thoroughly as a future exploration.

5. Conclusions

The proposed conceptual experiment uses the industrial robot arm to produce structures by stacking unit bricks without comprehensive hard-coded instructions for the form – blueprints from the outset. The user provides only a rough boundary area for a stacking and a unit brick's material property at the beginning of the process. The proposed system uses simple rules of physics based on the given material property and stochastically finds and places new bricks on top of an existing structure in available positions. By repeating this stochastic selection based on dynamics, the robot can produce a number of schemes that can satisfy the primary requirement.

The proposed method for robotic fabrication is considered to be effective for dynamic scenarios where the conditions of the sites are subject to continuous environmental changes. The system can concurrently foresee a few possible scenarios based on the ever-changing conditions, and this dynamic adaptation does not always exist in typical blueprint-based human constructions. In principle, users can apply more complex and multiple constraints such as lighting and density for the production of schematic structures by the robot without giving a complete set of formal instructions. Figure 8 shows one such example: the placements of new cells are based on an overall number of openings to outdoor spaces using a similar stochastic selection process inspired by a process of accretion over time called Diffusion-limited Aggregation. Although this sole computational example does not use robotic fabrication and the stacking of bricks, this suggests the possibility of implementing more complex objectives for the resulting structures.

Another potential future improvement can be adding reconfigurability and an active real-time feedback system for its subunits – bricks for robotic fabrication. In principle, a robot can continue to optimize the structure's performance even after the completion of the initial structure. Figure 9 shows the robotic prototype with

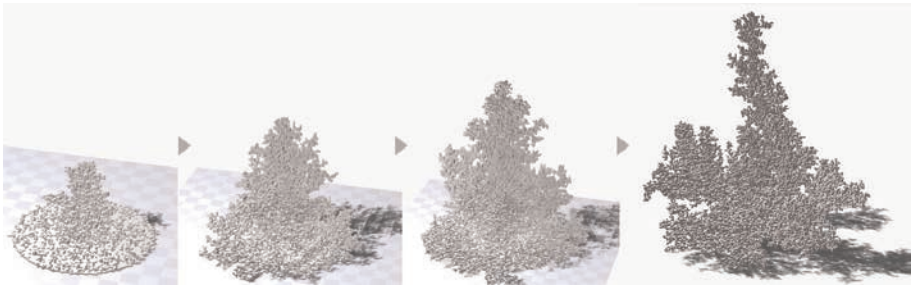

Figure 8. Algorithmically optimized 3-D clusters with maximized opening areas using DLA.

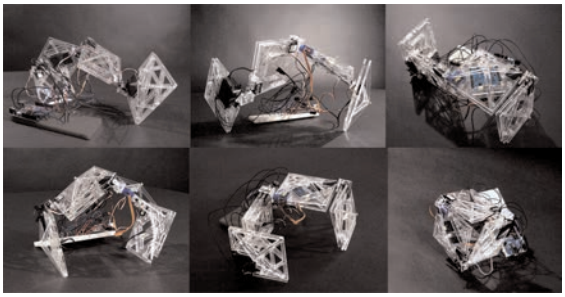

Figure 9. Reconfigurable robotic device with locally embedded sensors and microcontrollers.

locally embedded sensors and microcontrollers; its bottom-up control strategies allow the device to optimize its orientation with respect to a light source, independent of how and where the unit is placed. The same logic can be implemented to the robotic fabrication by reconfiguring bricks using a robotic arm based on local sensing of various properties obtained from embedded sensors inside each brick. In theory, this will produce an active assembler and assemblee relationship that can constantly adapt and grow a structure based on changes in physical/environmental constraints, programmatic/social issues relating to occupancy types, social issues, programs, and code/zoning constraints, and so on.

In contrast to a construction based on hard-coded predefined instructions, a robot arm with cognitive capabilities – a sensing robot arm with devices such as a real-time camera feed – or an active construction module such as a sensible brick can be viable options for future explorations, as they can concurrently generate instructions, based on the current state of the system, to spontaneously adapt to change its goal for globally optimal performance. In addition to the simple physics introduced in the paper, for example, the system can sense the adjacent on-going constructions gradually obstructing and changing the lighting condition of the site and flexibly create instructions for the next growth.

The primary systems architecture of the robotic experiment in this paper is still reliant on a single agent and has yet to acquire multiplicities that can be observed in collective construction. Realizing bottom-up growth using robotic devices may require implementation of a distributed multiple-intelligence system, and the above Figure 9 shows some possibilities by locally embedding sensors to components constituting a whole (Narahara, 2010). As a reference, the author has software-based generative experiments based on a multi-agent system in the context of urban design with comparisons to other existing methods such as shape grammar (Narahara, 2013).

The research in this paper is not ready to provide a direct application to existing architecture. It is, rather, at the stage of finding the right instances of

applications in architecture. Finding scenarios that require gradual growth over time in architecture is practically a challenge. Except for some urban-scale developments, the scale of physical size and the magnitude of time that it takes to grow for buildings have not reached a level where we require such a design method. In most cases, practitioners can forecast sufficient solutions analytically, and are very unlikely to find any kind of building development that requires step-by-step constant improvements in shorter segments of time (as in some spontaneous settlements). Practical and functional needs for our current structures, and the technology and economy to support the realization of such structures, seem not yet to have reached the stage where evolutionary processes can be fully and effectively utilized.

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References

Alexander, C.: 1965, A city is not a tree, I, II, *Architectural Forum*, **122**(1), 58–62, **122**(2), 58–62.

Brand, S.: 1994, How Buildings Learn: What Happens After They're Built, Viking, New York.

Camazine, S., Deneubourg, J.-L., Franks, N. R., Sneyd, J., Theraulaz, G. and Bonabeau,. E: 2002, *Self-organization in Biological Systems*, Princeton University, Princeton, NJ.

Gramazio, F. and Kohler, M.: 2011, Architecture and digital fabrication, Jahrbuch / Yearbook 2011, Department of Architecture, ETH Zurich, 174–177.

Grasse, P.: 1959, La reconstruction du nid et les coordinations inter-individuelles chez bellicositermes natalensis et cubitermes . sp. la theorie de la stigmergie: essai d'interpretation du comportement des termites constructeurs, *Insectes Soc.*, **61**, 41–81.

Zykov, V., Mytilinaios, E., Adams, B. and Lipson, H.: 2005, Robotics: self-reproducing machines, *Nature*, **435**(7039), 163–164.

Narahara, T.: 2010, Designing for Constant Change: An Adaptable Growth Model for Architecture, *International Journal of Architectural Computing*, **8**(1), 30–40.

Narahara, T.: 2013, The Computer as a Tool for Creative Adaptation: Biologically Inspired Simulation for Architecture and Urban Design, *in* J. Zander and P. Mosterman (ed.), *Computation for Humanity—Information Technology to Advance Society*, 1st ed., CRC, Boca Raton, FL.

Parish, Y. I. H., and Muller, P.: 2001, Procedural modeling of cities, *in* E. Fiume (ed.), *Proceedings of ACM SIGGRAPH 2001*, ACM, 301–308.

Theraulaz, G. and Bonabeau, E.: 1995, Modeling the collective building of complex architectures in social insects with lattice swarms, *Journal of Theoretical Biology*, **177**, 381–400.

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ROBOTIC FABRICATION OF MODULAR FORMWORK

An innovative approach to formwork fabrication for non-standard concrete structures

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Abstract. In this work we address the fast and economical realization of complex formwork for concrete with the advantage of robotic fabrication. Under economical realization we mean reduction of production time and material efficiency. The complex form of individual formwork parts can be in our case double curved surface or complex mesh geometry. We propose the fabrication of the formwork by straight or shaped hot wire. We illustrate different approaches to mould production, where the proposed process demonstrates itself effective. In our approach we deal with the special kinds of modularity and specific symmetry of the formwork.

Keywords. Robotic fabrication; formwork; non-standard structures.

1. Introduction

The recent advance of CAD/CAM technologies has considerably blended the transition between the digital and its physical counterpart. Efficiency of the process becomes less crucial, as the data can nowadays be almost effortlessly processed, giving predominance to customization of the produced parts. However, the industry still cannot manufacture the building as a single part, which results into an unavoidable issue of fragmentation. Thus, even though the designing of free-form architecture has been for architects easier to access, the building must be divided into set of parts which are subdivided into another set of parts, and so on. For example, one global fragment is the facade of these buildings, further locally subdivided into many different parts. The most common technique is to discretize the curved shape into planar elements, which requires techniques that have been researched in the last decade (Eigensatz et al., 2010; Pottmann et al., 2008a; Shelden, 2002). Without discretization needs to be for every part produced costly

formwork, whether it's for glass, concrete or other material. The problem of these techniques is that for every part of the facade must be created a unique mould. The most common type of formwork is the polystyrene (EPS or XPS) mould which is 3D formed using a CNC milling machine. This technique is very accurate, but it requires time and produces a lot of waste material. On the other hand, the polystyrene is commonly cut fast and with minimum waste by heated wire, especially when both sides of the cut foam can be used. Therefore, the aim of this project is to explore the mould forming of complex geometries by using a hot wire cutting technique that can potentially diversify and spatially enrich the repetitive aspects of modular systems still pertinent in the production of architecture today. Can we make a use of hot wire cutting technique operated by industrial robotic arm to create a complex mould while minimizing the production time and the waste material?

2. Designing the Negative

2.1. CONCRETE AND FORMWORK

Being an amalgam, concrete does not have any implicit shape; it can be moulded into any form imaginable. Also the steel reinforcement does not have significant embedded constrains. This suggests the possibility of a biomorphic utility of reinforce concrete, similar to working with clay. However, the limitation lies in the formwork, characteristic by its rigidity.

Ideally the form finding of a load bearing structures origins in complexity of structural logic, but the most often reality is that the resulted shape is blend of structure and the most economical formwork achievable. As an attempt to lower the cost to minimum, over the past, the construction has developed into modular and reusable formwork layout (Figure 1a,b), which unfortunately fails when each formwork differs in shape (Figure 1c).

2.2. HOT WIRE

The hot wire cutting technique uses typically straight heated wire. This constrains the design process into ruled surface geometry, as the ruled surface is formed by continuous sequence of straight line segments. Ruled surfaces already have been used in creating complex architectural forms. One example is the pioneering work of Antoni Gaudi and his Sagrada Familia Cathedral ("Ruled Surfaces", n.d.). The hyperbolic paraboloid geometries of the cathedral's ceiling vault system are ruled surfaces that can be created by using hot wire. However, the wire can be also shaped to research beyond the ruled surfaces and to explore more geometrical possibilities.

Figure 1. From left – a: Miguel Fisac with his pre-cast pre-stressed concrete elements, b: reusable forkwork, c: "Urban nebula" – concrete bench by Zaha Hadid.

2.3. ROBOTIC FABRICATION

The big challenge was the optimization of the robot data flow from parametric design to a physical model. A Grasshopper component was generated within the project that included inverse kinematics and all the necessary calculation for direct robot programming with an automatic code generation. The basic robot code was supplemented with special strategies depending on individual specific design meant to facilitate the transformation of the desired design to the basic robot code. This approach provided great flexibility in design and real time feedback to the designer due to the robot constrains. The used industrial robotic arm – Robot ABB IR140 constrained the cutting size into 250x250x160mm EPS blocks (Figure2) that could be to cut into stackable ornamental components, which then composed the negative form-work for the concrete wall design.

These constraints necessitated the adaptation of the individual design, starting with changes of the initial design, selected tool or EPS tool cutting strategy. Since one of the projects aims regarded cost-effective use of materials, the first part of

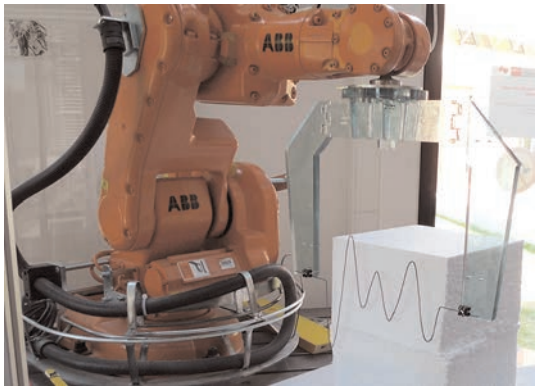

Figure 2. Robot ABB I140.

the research was started with modular ornamental parametric elements. By varying their parameters and positions it was possible to obtain a huge number of variations of the final design.

3. Patterning

Patterns can be found in different parts of a building. In "The Self-Made Tapestry", Philip Ball describes patterns as "arrays of units that are similar but not necessarily identical, and which repeat but not necessarily regularly or with a well–defined symmetry" (Ball, 1999, p. 9).

3.1. P4 SYMMETRY

3.1.1. Periodic tilling

The tiling is based on a symmetry group *p4* (Figure 3). This symmetry group has two-fold rotation (in points A and C) and two four-fold rotations (in points B and D) – Figure 3a.

Geometrically the p4 border pattern consists of two curves *a* and *b*. These two curves are rotated around points B and D for 90° in order to generate border curves. The 3d shape is generated by extrusion of pattern in the direction normal to the plane

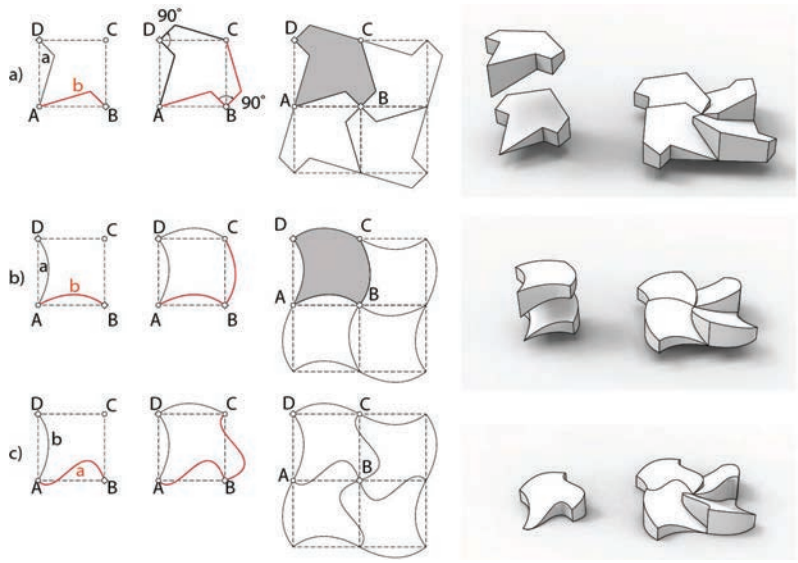

Figure 3. Variation examples and assembly of p4 parts.

Figure 4. Assembled foam blocks – positive cut.

ABCD. The used 3D form is optimised and enables cost–efficient use of material and time efficient cutting technique. The three–dimensional form was achieved with the cutting of boundary box with one symmetry plane that divided block into two parts. The second cut was the shape cut of 2D pattern that makes final shape. Generally for this symmetry group the both base curves can have different shape (Figure 3c), which opens other possibilities and freedom in the design process.

With only two cuts, it is possible to get four elements, two positives and two negative parts of the desired pattern. Negatives are used as formwork for concrete, while the positives can be used as an insulating facade element (Figure 4). This shape also enabled over lock between the individual moulds in the four–fold rotational point that has a positive static influence onto whole assembling structure.

3.1.2. Aperiodic tiling

Aperiodic tiling has been discovered on quasicrystals and can be generated by projection of higher dimensional grids into two or three dimensions. Theoretically there can be infinite different patterns in one plane without any holes that are able to be continued indefinitely. They are comprised of structures made of few different tiles which are combined in a non-repetitive manner. Rotational symmetry makes their non-repetitive combination possible as opposed to periodic structures which only have translational symmetry (can be copy and paste next to each

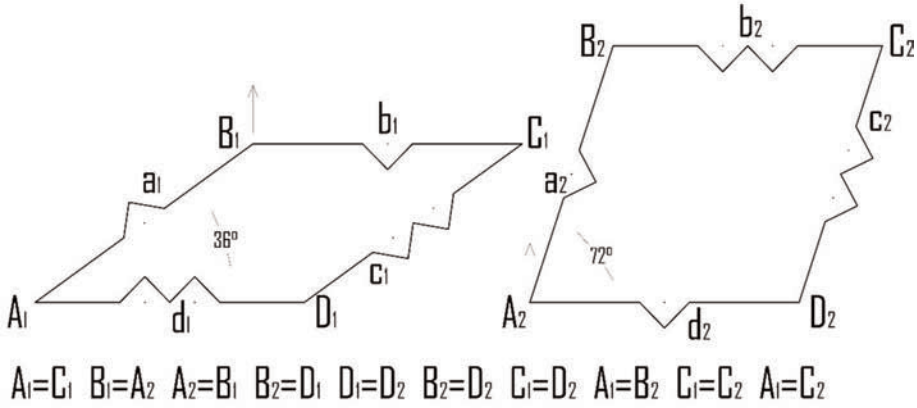

Figure 5. Penrose basic tiles – combining rules and their impact on the relocation of corners in z-direction and the shape of edges.

other). An example of aperiodic tiles is the Penrose tiles, discovered by the British mathematician Roger Penrose in the 1970's prior to the discovery of quasicrystalline structures in 1984. The Penrose tiling can be derived from the projection of five dimensional grids onto a two dimensional plane (De Bruin, 1981). The growth of the tiling is regulated by a finite number of (local) matching rules between tiles (Figure 5). In the pattern *a1 = b1* and *a1 = c1 = d2 = b2 = d1 = c2*. The B1 and A2 corners can be moved into the z-direction by equal value. Another *z*-value has to be used equally for the other corners. All of the edges which are coming from the vertex shifted in *z*-direction have to be identical. Each of the other corners has to be mirrored around their centre.

This formwork for this tiling can be created by assembly of two different shapes in the form of rhombuses, one with the corner angles of 72° and 108° and the other with corner angles of 36° and 144°. The height of the corners of those two rhombuses has to be the same in order to form continuous surface, but the shape of the edges can be arbitrary. Figure 6 shows the generation of such pattern. The main pattern consists of only two different curves *a* and *b* that are rotated around points A and D for 72° and points C and F for 144°. Actually, one can choose any two different border shapes in order to generate pattern with the penrose symmetry. In 2D generated form is the main penrose cell (Figure 6a, b, c) which borders are straight lines.

The 3D form is generated shaping 3D EPS block using rotation in the points A and F. This rotation is a space rotation of the straight line along space curve *c* (Figure 6d). This kind of generation allows cutting the EPS blocks with the hot wire, but a shaped hot wire can be also used in order to design possibility. Figure 7 shows formwork for 3D Penrose pattern.

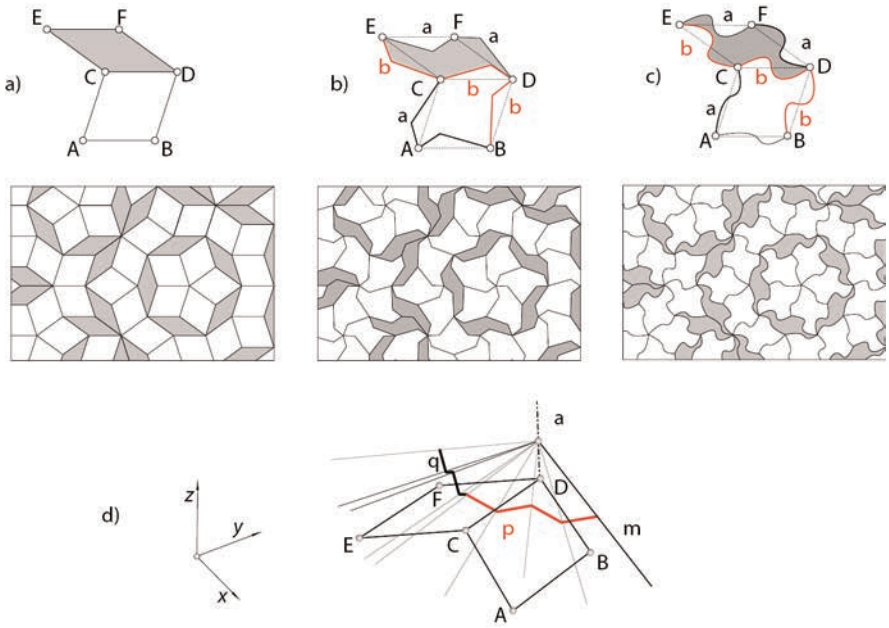

Figure 6. Penrose tiles – different tile patterns derived from basic Penrose tiling rule.

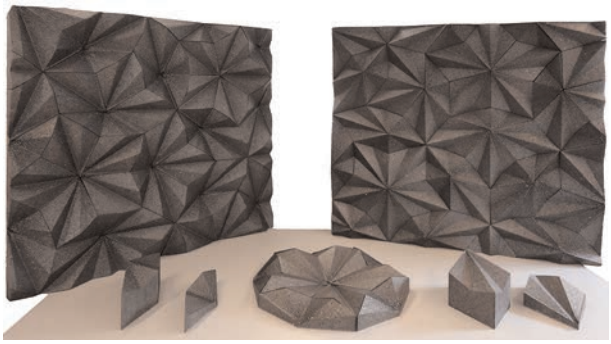

Figure 7. Formwork for Penrose pattern.

3.2. ANTIPRISM

In this study case, the geometry is topologically based on using antiprism as the base element which can be modified and organized in order to achieve structural stability (Figure 8a).

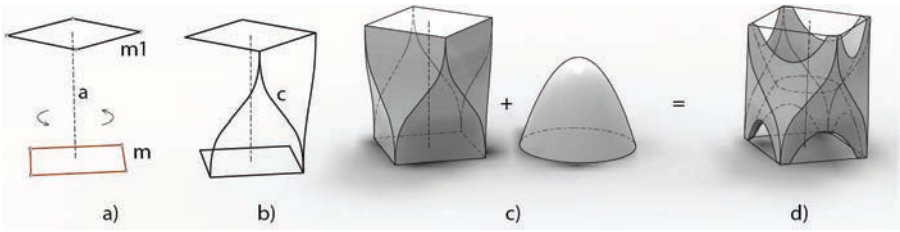

Figure 8. Strategy of creating component based on antiprism.

Figure 9. Morphology of the column.

The *n*-sided antiprism is the result of rotating the base *m* by an arbitrary angle around axe *a*. Such a 3D form can we generated by twisting a cube around one axes that is parallel with four cube edges. In our case the geometry is based on either square antiprism (Figure 8c, 8d), the anticube, or on triangular prismoctahedron. The bottom base *m* and top base *m1* can be connected by triangular faces which edges can be further modified by splines curve to generate different shapes (Figure 8b). Therefore, the element can be formed out of ruled surfaces that can be fabricated by the straight hot wire. Inside of the antiprism the rotational paraboloid is parametrically generated and subtracted from it. Because the base and the top faces can be independently scaled, it is possible to create variety of fluidly formed columns out of those stacked elements (Figure 9).

Each cut can be done precisely and fast with minimum manipulation of the foam block between cuts (Figure 10). Figure 11 presents cut order and their paths, Figure 12 formwork assembly with resulted concrete part.

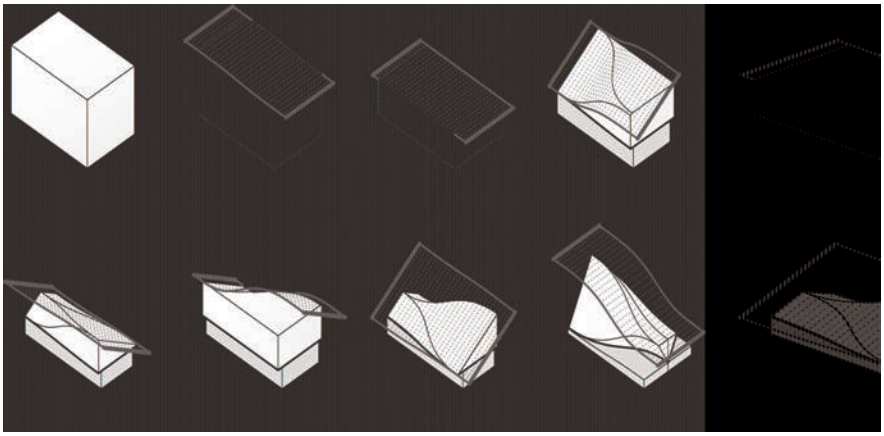

Figure 10. Cut diagram and assembly of formwork.

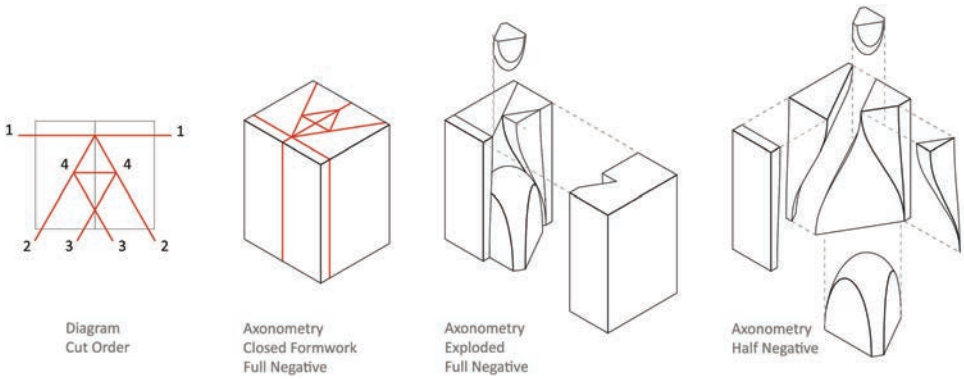

Figure 11. Cut order and paths for the robotic arm.

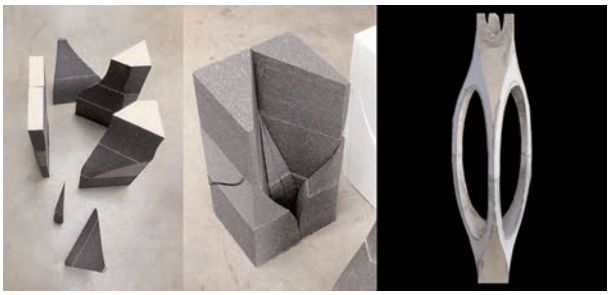

Figure 12. Formwork assembly and resulted concrete part.

4. Outlook

We performed static load analysis which demonstrated that the geometry can withstand substantial stresses. Therefore, the component could be used as load bearing building element (Figure 13).

Figure 13. Stacked elements creating load bearing wall.

We are currently working on fabricating full scale prototypes out of ultra-high performance concrete to test the precision, and the obtained surface quality. We are also developing a joint system as we anticipate that the jointing between the components will become a critical part of the assembly process. The digital methodology of obtaining the geometry will definitely benefit from the data collected during the physical assembly of the prototypes.

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References

Ball P.: 1999, *The self-Made Tapestry: Pattern Formation in Nature*, Oxford.

De Bruijn, N. G.: 1981, Algebraic theory of Penrose's nonperiodic tilings of the plane, I, II, *Nederl. Akad. Wetensch. Indag. Math.*, **43**, 39–52, 53–66.

Eigensatz, M., Deuss, M., Schiftner A., Kilian, M., Mitra, N. J., Pottmann, H. and Pauly, M.: 2010, Case studies in cost-optimized paneling of architectural freeform surfaces, *in* C. Ceccato, L. Hesselgren, M. Pauly, H. Pottmann, and J. Wallner, (eds.), *Advances in Architectural Geometry 2010*, Springer, Vienna, 49–72.

Pottmann, H., Schiftner, A., Bo, P., Schmiedhofer, H., Wang, W., Baldassini, N. and Wallner, J.: 2008a, Freeform surfaces from single curved panels, *ACM Transactions on Graphics*, **27**(3).

"Ruled surfaces": n.d. Available from: <http://www.sagradafamilia.cat/sf-eng/docs_instit/pdf/geom_02.pdf> (accessed 22 March 2013).

Shelden, R. D.: 2002, Digital Surface Representation and the Constructability of Gehry's Architecture, Ph.D. Dissertation, Massachusetts Institute of Technology, Cambridge, MA.

GENERATIVE AND EVOLUTIONARY DESIGN 1

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GEOMETRIC COMPLEXITY AND ENERGY SIMULATION

Evolving Performance Driven Architectural Form

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Abstract. The research presents the custom development of a software tool and design process for integrating three design domains, their respective objectives, and geometric parameterizations. It then describes a set of experimental projects and analyses in the context of informing form and geometric complexity. Preliminary results of the multidisciplinary design optimization prototype, which, implements a genetic algorithm, are then presented. The findings include discussion of the value for architects for designing-in performance e.g. the bringing of the energy simulation and financial pro-forma upstream in the design process and of the value for trade off design decision making the system provides. The summary discussion includes the benefit of breeding architecturally complex geometries and the kinds of optimisations or search for improvements on designs that can be achieved.

Keywords. Parametric; generative; optimisation; design decision support.

1. Introduction and Motivation

Our research looks to the notion of informing form in the context of heightened awareness and necessity for performance in architecture, urbanism, and building systems. As a foundational mind set, the research builds upon associative parametric design methodology, as a solution space approach incorporating multiple design domains and criteria. The method and technology presented enables an expansive creation of design solutions sorted, bred, and optimised to meet the demands of architectural human computer interaction- the design act- and the oft-competing design objectives. Given our architecturally centric approach, the limitations of design cycle times and project complexity become less of a barrier and yet the problem of solution ranking and qualification become paramount. The

research builds upon earlier design integration research and acknowledges the necessity of domain specialization and expertise. The research presented here stems from a focus on early stage design decision making and the desire to inform these early design decisions with rapid and more accurate performance e.g. energy awareness specifically for architects. At the intersection of energy simulation with design geometry and process the work looks to improving upon our empirical understanding of environmental impact while protecting and supporting architectural ingenuity and its geometric complexity. While current modes of practice do include energy simulation, generally it is inconsistent or sporadic and rather implemented post facto with respect to the analysis of architectural geometry and form (Crawley et al., 2008; Schlueter and Thesseling, 2009). It is with the advancement of parametric design technologies and algorithmic search techniques that the research focuses on the abilities to rapidly generate and explore design options. Design exploration is at the core of the research where design is understood to be multi-objective and requisite of designer driven logical structures and choice (Ren et al., 2011). Fundamentally, the research addresses the challenge that design complexity is no longer solely the geometry itself but how to incorporate performance feedback into design decision-making process.

2. Background and Review

At the outset for the research contemporary design process faces pervasive and deep-rooted limitations with respect to incorporating and more so correlating energy simulation with complex geometry. These limitations are in some part related to tools and interoperability, domain knowledge integration (Malkawi, 2005), and design cognition and complexity all of which contribute to design uncertainty, waste and design cycle latency. Our work is situated through four primary precedent categories; parametric design and design exploration; performance simulation and feedback; multidisciplinary design optimization (MDO); and evolutionary design techniques. Intrinsic to our interest, the research acknowledges design process as being inherently complex, and one that requires iteration and exploration (Eastman, 1970). As one begins to add energy simulation and other performance criteria earlier into the design process the complexity compounds for the designer to manage.

2.1. PARAMETRIC DESIGN AND DESIGN EXPLORATION

A fundamental building block for our research is the use of parametric design and modelling for rapid design iteration (Gero, 1990). Furthermore parametric design thinking and modelling enables relational i.e. correlative, integral and explorative

design process (Menges, 2011). Important to the research is the understanding that iteration can increase the possibility for finding higher performance designs through the notion of design exploration of both geometric and their non-geometric variables according to established design objectives and constraints (Shea et al., 2005). One recent precedent utilized the parametric form generation process to find various performance envelopes and demonstrated promising capability to support design decision making.

2.2. PERFORMANCE SIMULATION AND FEEDBACK

While constructability is often the first issue to be tackled by designers in developing complex geometry (Glymph et al., 2004) our focus along with others is to append this obvious need with that of informing these forms with performance criteria such as energy use intensity, project economics or environmental footprint. This is especially important in the early design stage where the decision made has a significant impact on the life-cycle cost of buildings (USGBC, 2003). The use of performance simulation is not a novelty to the field of architecture, but previous studies show that performance-based analysis methods conventionally adopted rarely are able to support these early stage design decisions due to time limitation. Augenbroe summarises current needs of the building simulation tools and concludes our focus should be on; 1) rapid evaluation of alternative designs; 2) tools to support decision making process; and 3) improving designers ability to solve nonlinear and multi-criteria problems (Augenbroe, 2002). Recent efforts to improve the integration of the design process and the energy performance domain include: combining a parametric design environment with a spread sheet calculator to provide real time performance feedback (Sanguinetti et al., 2010); and the ParaGen project, which explored a performance based design process by combining parametric modelling and genetic algorithms correlating structural performance and solar energy (Turrin et al., 2011). Yi and Malkawi developed a method to apply energy performance feedback to complex geometry by defining hierarchical relationship between geometry points (Yi and Malkawi, 2009). Other recent works have focused on the early stages of building design to fulfil energy performance requirements through parametric definitions (Toth et al., 2011).

2.3. MULTIDISCIPLINARY DESIGN OPTIMIZATION (MDO)

Multidisciplinary design optimisation (MDO) refers to optimisation methods used to solve design problems with multiple objective functions and that incorporate a range of disciplines (Coello Coello et al., 2007). As defined by Poloni, MDO is “the art of finding the best compromise” (Poloni and Pediroda, 1997). One precedent

investigates the application of a multi-objective genetic algorithm (MOGA) for finding the optimal in the trade-offs between capital expenditure, operation cost and occupant thermal comfort in building design. Others tested MDO in a building design setting with thermal, structural, financial and environmental performance evaluation by integrating all the platforms via an IFC scheme (Geyer, 2009). Magnier uses the approach to optimize the energy consumption and thermal comfort of a residential building (Magnier and Haghighat, 2010). The "CATBOT" project utilized MDO to link complex geometry to structural analysis (Keough and Benjamin, 2010).

2.4. EVOLUTIONARY DESIGN TECHNIQUES

The invention of evolutionary algorithms can be traced to the work of John Holland (Holland, 1992) and genetic algorithms (GA) to Goldberg's work (Goldberg, 1989). The development of an influential evolutionary architectural theory and application of GA and evolutionary process on complex geometry is that of John Frazer's work (Frazer, 1995). Another seminal application of GA to design research and environmental performance for multi-objective design problems is that of John Gero; critical to note is his use of Pareto optimisation to enable design decision making (Gero et al., 1983). Recent example of environmental applications of GA to multi-objective design optimization problems include the integration of CFD analysis and the coupling of indoor comfort factors to external climate (Huang et al., 2012) along with an investigation into the practicality of design applications that used evolutionary algorithms to generate and filter design options (Krish, 2011). Our research builds upon the use of GA for design optimisation to search for a set of better-fit solutions in which a synthetic trade off decision must be made by the human designer or team.

3. The Prototype the 'H.D.S Beagle'

H.D.S. Beagle (the Beagle) integrates the three design objectives through an integrated and evolutionary process. The three objectives of interest in this research are energy, financial and spatial programing compliance performance. The selected respective performance measurements are energy use intensity (EUI), net present value (NPV), and spatial programing compliance score (SPC). In order to support the form generation in concert with these three performance feedback in a semi-automated -directed search- there are three key activities that comprise the Beagle; 1) initialising the model through parameterisation; 2) integrating the domain specific analysis engines; and 3) the automation of the generation of evolved i.e. improving design variants through the genetic algorithmic search and

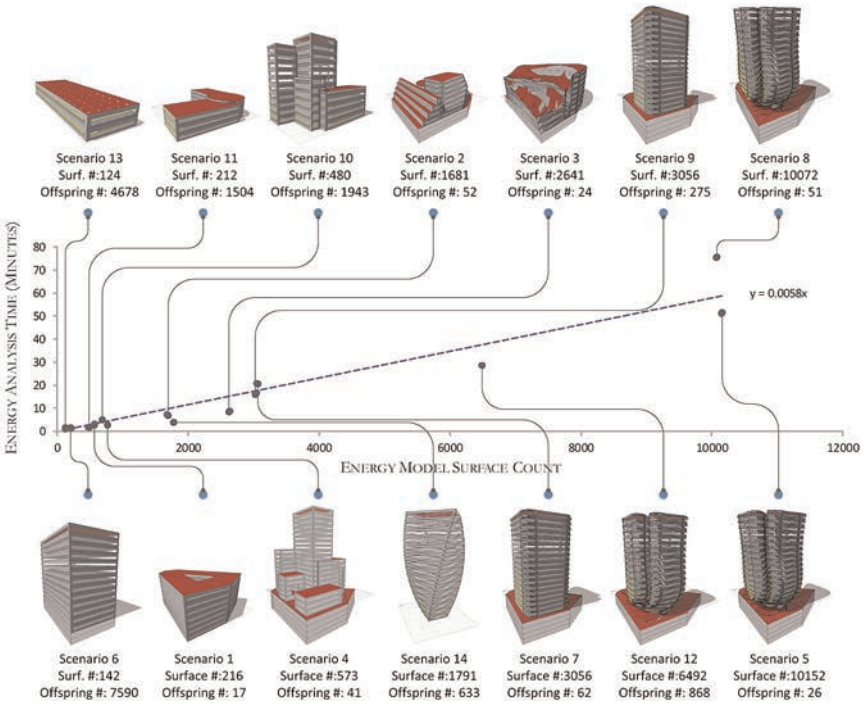

Figure 1. The graph illustrates the relationship between geometry surface count and energy analysis time. A sampling of the scenarios and their offspring counts are overlaid on the graph. The 3D images are the visualisations of each scenario' tessellated energy model.

Pareto optimisation. The full description of the tool and tool development is in our previous publication (Gerber and Lin, 2012).

4. Experiments and Analysis

The research team has developed 14 cases to date to test the Beagle from simple to complex geometries. The intent was to explore surface geometry in terms of the ambiguity i.e. designer uncertainty as they relate to energy use intensity. A summary of this spectrum can be observed in Figure 1. All results are then analysed via empirical measurements across scenarios but also via process map comparisons in order provide more certain understandings of the performance characteristics of a particular complex geometry. By counting the number of offspring and generations and then comparing surface count of each scenario's initial energy model to time we plotted the design cycle latency effect, as illustrated in

Figure 2. There are various factors that impact the energy analysis time, such as the time needed for the translation of a geometric model into an energy model or to provide said energy model to the GBS for analysis as well as Internet stability. Conventional energy simulation software and methodology rarely support a designer's interest in scale of the possible design exploration and in particular the impact of overall geometric form coupled with the multiple objectives. As a result, in order to observe the potential benefit to include form exploration in the process, four variations of scenario 14 (Figure 2) are tested by exploring the same energy parameters and project requirements. Climate data and site related information is provided by the same hypothetical site. These four models are designed as a mixed used building to fulfil the requirement of 11,000 sqft retail space, 20,000 sqft office space and 10,000 sqft hotel space. The three explored energy related parameters are: 1) "Target Percentage Glazing" ranging from 20%~80%; 2) "Shade Depth" ranging from 0~3ft (0~0.9m); 3) "Target Percentage Skylights" ranging from 0%~60%. The results show the benchmark energy performance for model (a) is 145 kBtu/ft^2/yr (457kWh/m^2/yr). The solution space range for model (a) when varying the 3 parameters is 101 ~ 236 kBtu/ft^2/yr (319~744kWh/m^2/yr). Then we compared the case of model (a) including geometric variation, illustrating the exploration of building form, better energy performance as a minimised EUI ranging from 46~132 kBtu/ft^2/yr (145~416 kWh/m^2/yr) is found. Next, we increased the complexity of the building geometry to measure if the performance will improve. In model (b) we add the scale factor on top of the building footprint; in model (c) we add another scale factor in the middle of the building footprint; lastly, in model (d) we add the rotation parameter to explore even more complex geometry. From the results in Figure 2 we find model (d) provides solutions with better energy performance through the EUI values. Model (d) also provides better financial and design scores solutions when compared to the first three model settings. Figure 3 model (d) has the most complex geometry including double curvatures but as well seems to provide a higher performing solution space when the Beagle is run resulting in a range of 44~209 kBtu/ft^2/yr (139~659 kWh/m^2/yr). It should be noted that current financial model does not reflect the additional structural cost from the increase of geometric complexity. However, the current experiment does demonstrate that our searching method and form exploration provide opportunities to finding better performance solutions.

In order to evaluate process improvement of the Beagle four different process maps are summarized according to our current experimental, pedagogy and case based experiments, as shown in Figure 3. For the four process maps, we specifically use five categories to evaluate the Beagle process improvement: 1) time required to generate a design model; 2) time required to generate an energy model; 3) time required to obtain the analysis feedback; 4) numbers of options to support

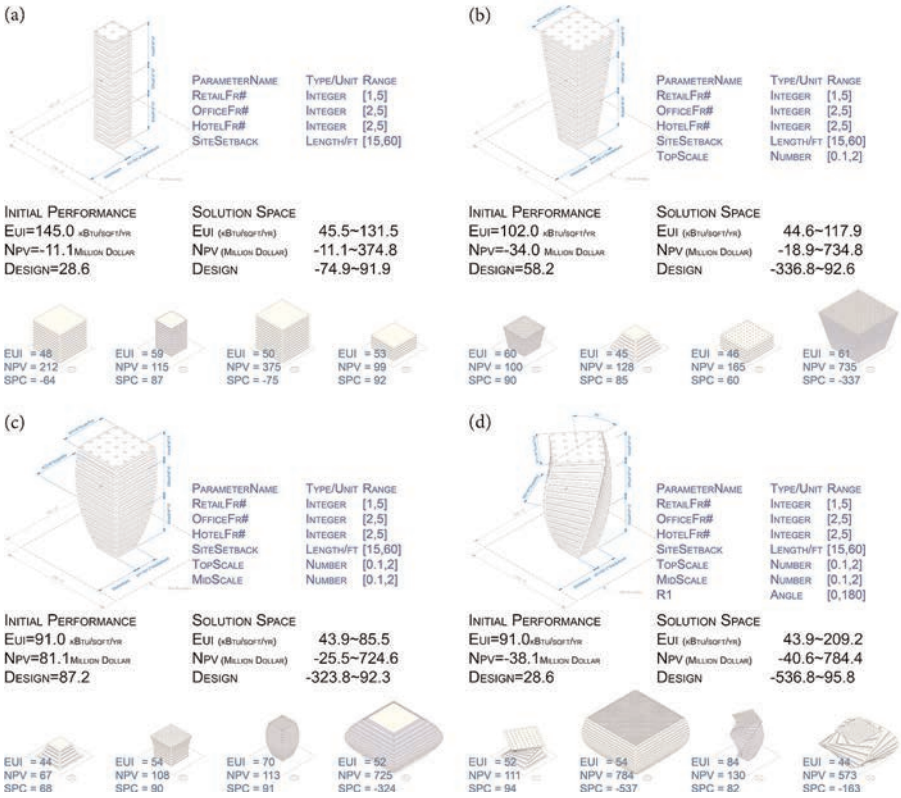

Figure 2. The table illustrates the improvements found in the energy performance feedback for scenario 14 as they relate to model geometric complexity.

decision making within a specific amount of time; 5) the ability to help solve the multi-objective problem. The results can be seen in Figure 3.

The first two processes are summarised from a case-based experiment, which highlighted the interoperability issues between design domain tool and energy simulation tool. In these two processes, the designer or the engineers have to create different model for energy simulation purpose. If any geometry changed, the energy model needs to be manually adjusted accordingly due to lack of parametric definition. In the first process map the time required to get the performance feedback is the longest (168 hours) and by the time the designer obtains the feedback result, the initial building form has been decided. Therefore the feedback can only have limited impact for the overall building geometry. The second process illustrates a more rapid feedback 6-hour cycle, however, is still not sufficient to

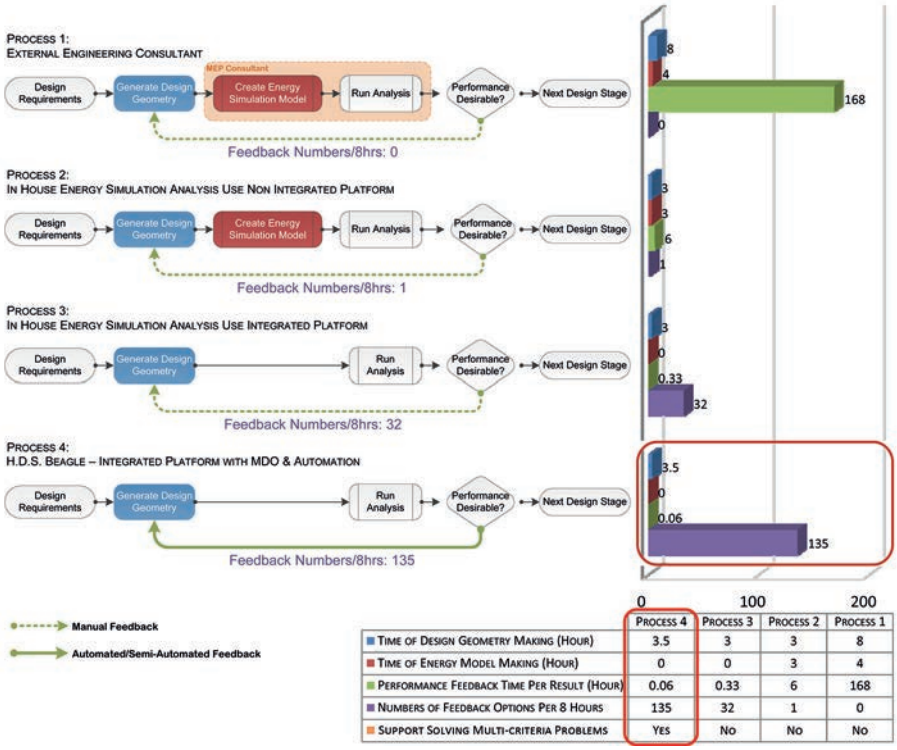

Figure 3. The four process map comparisons of energy simulation feedback and overall process improvements of the incorporation and correlation of complex geometry.

support design decision-making. The third is a process map summarized from a pedagogical experiment. The results suggest an increase in design feedback compared to the first two processes. This pedagogical experiment also observed the limit of human cognitive load when it comes to complex geometry and performance criteria i.e. problem scale and coupling. In our experiment, students were asked to design explore by varying 9 parameters; 5 driving the geometry with the other 4 being energy related. The objectives as with all scenarios are to minimize EUI, maximize NPV and maximize SPC. However, the observed variety in novice exploration processes provided limited feedback to support decision-making.

We then compared these process maps and the pool of models to the Beagle process – process 4 in Figure 3. By comparison, through the selection of best fit individuals from each generation to provide the basis for the next generation, the Beagle provides more design options as well as improved EUI, NPV and SPC.

5. Conclusion and Discussion

The research illustrates an increase in a designers' ability to foresee the performance behaviours and therefore enhance architectural geometric complexity critical to being in step with contemporary energy use intensity demands. Our current findings suggest that the Beagle consistently evolved offspring towards more optimal solutions; where energy performance is improved by up to 50% sometimes and yielding highly non-intuitive but architecturally interesting forms. The affordances that the research empirically document include the increase in size of solution space and possible better fit solutions; the speed in which designs are generatively and rapidly iterated upon in terms of evaluation; the addressable scale of the problem i.e. our ability to tackle complex formal analysis; and the simultaneous visualization of the design criteria and the their trade-offs. What the research most successfully seems to suggest is that project objectives such as geometric complexity when coupled with energy simulation are best understood through an MDO supported design process. Otherwise designers cannot manage the complexity cognitively and will not be given the chance to optimise while in geometry generation stages. Fundamentally the Beagle provides the performance feedback irrespective of this geometric complexity, it is agnostic to the amount of surfaces or topology.

References

Augenbroe, G.: 2002, Trends in building simulation, *Building and Environment*, **37**(8-9), 891–902.

Coello Coello, C. A., Lamont, G. B. and Van Veldhuisen, D. A.: 2007, *Evolutionary algorithms for solving multi-objective problems*, Genetic and evolutionary computation series, 2nd ed., Springer, New York.

Crawley, D. B., Hand, J. W., Kummert, M. and Griffith, B. T.: 2008, Contrasting the capabilities of building energy performance simulation programs, *Building and Environment*, **43**(4), 661–673.

Eastman, C. M.: 1970, On the analysis of intuitive design processes, in G. T. Moore (ed.), *Emerging Methods in Environmental Design and Planning*, MIT Press, Cambridge, MA.

Frazer, J.: 1995, *An evolutionary architecture*, Architectural Association, London.

Gerber, D. J. and Lin, S.-H. E.: 2012, Designing-in performance through parameterization, automation, and evolutionary algorithms: 'H.D.S. BEAGLE 1.0', *in* T. Fischer, K. De Biswas, J. J. Ham, R. Naka and W. X. Huang (eds.), *CAADRIA 2012: Beyond Codes and Pixels*, Chennai, India, 141–150.

Gero, J. S.: 1990, Design prototypes: A knowledge representation schema for design, *AI Magazine*, **11**(4), 26–36.

Gero, J. S., D'Cruz, N. and Radford, A. D.: 1983, Energy in context: A multicriteria model for building design, *Building and Environment*, **18**(3), 99–107.

Geyer, P.: 2009, Component-oriented decomposition for multidisciplinary design optimization in building design, *Advanced Engineering Informatics*, **23**(1), 12–31.

Glymph, J., Shelden, D., Ceccato, C., Mussel, J. and Schober, H.: 2004, A parametric strategy for free-form glass structures using quadrilateral planar facets, *Automation in Construction*, **13**(2), 187–202.

Goldberg, D. E.: 1989, *Genetic algorithms in search, optimization, and machine learning*, Addison-Wesley, Reading, MA.

Holland, J. H.: 1992, *Adaptation in natural and artificial systems: An introductory analysis with applications to biology, control, and artificial intelligence*, A Bradford Book, Ann Arbor.

Huang, H., Kato, S. and Hu, R.: 2012, Optimum design for indoor humidity by coupling Genetic Algorithm with transient simulation based on contribution ratio of indoor humidity and climate analysis, *Energy and Buildings*, **47**, 208–216.

Keough, I. and Benjamin, D.: 2010, Multi-objective optimization in architectural design, *in* A. Khan (ed.), *SimAUD 2010*, Orlando, FL, 5–12.

Krish, S.: 2011, A practical generative design method, *Computer-Aided Design*, **43**(1), 88–100.

Magnier, L. and Haghighat, F.: 2010, Multiobjective optimization of building design using TRNSYS simulations, genetic algorithm, and artificial neural network, *Building and Environment*, **45**(3), 739–746.

Malkawi, A.: 2005, Performance simulation: research and tools, *in* B. Kolarevic and A. Malkawi (eds.), *Performative architecture: beyond instrumentality*, Spon Press, New York, 85–96.

Menges, A.: 2011, Integrative design computation: Integrating material behaviour and robotic manufacturing processes in computational design for performative wood constructions, *ACADIA 2011 – Integration through Computation*, Banff, Alberta, 72–81.

Poloni , C. and Pediroda, V.: 1997, GA coupled with computationally expensive simulations: tools to improve efficiency, *in* D. Quagliarella, J. Périaux, C. Poloni and G. Winter (eds.), *Genetic algorithms and evolution strategy in engineering and computer science: recent advances and industrial applications*, John Wiley & Sons, West Sussex, England, 225–243.

Ren, Z., Yang, F., Bouchlaghem, N. M. and Anumba, C. J.: 2011, Multi-disciplinary collaborative building design – A comparative study between multi-agent systems and multi-disciplinary optimisation approaches, *Automation in Construction*, **20**(5), 537–549.

Sanguinetti, P., Bernal, M., El-Khaldi, M. and Erwin, M.: 2010, Real-time design feedback: Coupling performance-knowledge with design, *in* A. Khan (ed.), *SimAUD 2010*, Orlando, FL, 23–30.

Schlueter, A. and Thesseling, F.: 2009, Building information model based energy/exergy performance assessment in early design stages, *Automation in Construction*, **18**(2), 153–163.

Shea, K., Aish, R. and Gourtovaia, M.: 2005, Towards integrated performance-driven generative design tools, *Automation in Construction*, **14**(2), 253–264.

Toth, B., Salim, F. D., Drogemuller, R., Frazer, J. H. and Burry, J.: 2011, Closing the loop of design and analysis: Parametric modelling tools for early decision support, *CAADRIA 2011: Circuit Bending, Breaking and Mending*, Newcastle, Australia, 525–534.

Turrin, M., von Buelow, P. and Stouffs, R.: 2011, Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms, *Advanced Engineering Informatics*, **25**(4), 656–675.

USGBC: 2003, Building momentum: National trends and prospects for high-performance green buildings, U.S. Green Building Council (USGBC), Washington, DC.

Yi, Y. K. and Malkawi, A. M.: 2009, Optimizing building form for energy performance based on hierarchical geometry relation, *Automation in Construction*, **18**(6), 825–833.

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DYNAMIC TENSEGRITY SYSTEMS

Investigating a case in reconfigurable habitable structures

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Abstract. Irregular tensegrity structures, due to their non-linear behaviour, possess the potential ability to configure in multiple stable states. The kinematics and inherent properties of the compressive and tensile components govern the final static configuration of the system. The primary objective of the research is to study the non-linear behaviour of irregular tensegrity structures and formulate a computational generative, evaluative and algorithmic method to design a structurally dynamic tensegrity system, with inherent potential to adapt to the varying contexts and its respective demands, requirements and spatial needs.

Keywords. Tensegrity; non-linear systems; dynamic; generative algorithm; reconfigurable structures.

1. Introduction

1.1. NON LINEAR DYNAMIC SYSTEMS

Linear systems generally tend to be characterized by a single global state, but dynamic systems which are both non-linear and non-equilibrium, display multiple stable states that behave in a variety of additional forms, namely steady, periodic and chaotic states as explained in causality principle (Peitgen et al., 1992, p. 11). “We are beginning to understand that any complex system, whether composed of interacting molecules, organic creatures or economic agents, is capable of spontaneously generating order and actively organizing itself into new structures and forms”, says Manuel DeLanda (2004). It is precisely this ability of matter and energy to self-organize and exist in multiple stable states, which is of greatest significance due to its potential application to adapt to context. Neal Leach (2004) states, “in most advanced form, it would be an architecture that is open to those

processes themselves, as adaptive, responsive environment, that does not crystallize into a single, inflexible form, but is able to reconfigure itself over time, and adjust to the multiple permutations of programmatic uses that might be expected of it." The inherent morphogenetic property and variable behaviour of complex dynamic systems still remains to be studied, analysed and explored thoroughly to its complete potential in architectural context.

1.2. TENSEGRITY AS NON LINEAR DYNAMIC SYSTEM

Conventionally studied regular tensegrity structures can be classified as linear systems i.e. having a single global stable state based on number of struts and hence predictable in terms of solution. However, recent investigations in the field of developing and designing the tensegrity have led to identifying the complex non-linear behaviour of irregular structures (DeLanda, 2004). While the primary parameters governing the morphological stable state of the system are the properties of its compressive and tensile components, the connection logic and nodal degrees kinetic freedom of the configuration also contribute significantly to the resultant stability and morphogenetic variation. Irregular tensegrity structures having identical strut number and lengths can exist in variant morphologies based on connection logic and node forces.

1.3. SIMULATION OF TENSEGRITY STRUCTURES

Tensegrities are 3-dimensional stable mechanical structures that maintain its stability due to an intricate equilibrium of forces established between its rigid and disjoint compressive and continuous tensile components. They not only exhibit an exceptionally high strength-to-weight ratio but also possess the unique property of retaining its stability in zero-gravity (Williamson et al., 2002) spaces because the stable morphology is purely a function of its component properties and is irrespective of external forces. However, the determination of stable configurations that result from the connectivity patterns between the compressive and tensile components is highly challenging due to existence of multiple stable solutions. Thus the form-finding process of the tensegrity structures involves computational support juxtaposed with algorithmic approach to overcome the limitations of the available mathematical methods that have restricted scope of exploration (Paul et al., 2005, p. 3).

1.4. COMPARATIVE ANALYSIS

The primary difference between regular and irregular tensegrity structures is the uniformity and variation in the strut lengths respectively. A comparative analysis

between the regular and irregular morphologies, resulting from a set of preliminary experiments, concluded that regular morphologies only generated proportional volumetric and orientation variation when subjected to strut-length variation (applied uniformly). The regular geometries were also more predictable and behaved linearly (with single resultant stable state) as opposed to non-linear behaviour of irregular tensegrities which showed un-predictable variation in volumes, shapes, numbers, and stability of resultant morphologies. In spite of the non-linear behaviour, or rather, due to it, architecturally, irregularly generated morphologies could be spatially differentiated and hence more useful in contrast to the uniform, symmetrical, cellular and architecturally less usable spatial conditions of regular tensegrities. Also, the variation provided the potential of creating limitlessly varied morphologies for diverse design applications in various topological contexts. This characteristic diversity in irregularly generated modules also provides scope for higher complexity and further variation when organized in different hierarchical manner thus expanding its application at various scales (Ingber, 2003). These observations were key factors in narrowing the investigation on irregular tensegrity geometries to develop methods to predict and explore multiply stable forms with diverse spatial configurations and the respective architectural applications.

2. Generative Algorithm

This research uses generative algorithm to investigate the infinite solution space of irregular tensegrity structures, by digitally generating numerous random basic unstable seeds within certain parameters, and then relaxing them into all the possible stable relaxed states within the given set of connection logic using dynamic relaxation methods. The procedure involves use of dynamic relaxation for simulating the material properties and system performance while obtaining stable forms based on the input mechanical constraints and kinetic freedom. The rigorous analytical, evaluative, eliminative and selective procedure that follows the relaxation stage, aims at achieving optimal residual set of digitally developed and tested morphology modules that form the basis for next stage of design development aimed at organization logics of the emergent design.

2.1. PSEUDO-CODE

This step involved setting up the digital apparatus for the experimental exploration of irregular morphologies. Since the design domain was so wide and limitless, it was essential to fix the listed parameters to limit the boundaries of experiment, that involved first generating a widely variant set of unstable basic seeds, which

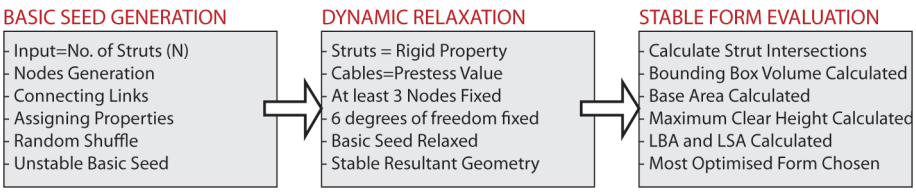

Figure 1. Pseudo-code for the generative algorithm.

would be later relaxed in its respective possible multiple stable states followed by intensive structurally evaluative elimination process. In order to generate randomly variant initial population, a generative script was written in Rhinoscript following the pseudo-code shown.

The first step involved generation of the unstable basic seed based on the input parameter of number of struts. In order to achieve a stable tensegrity structure, each node needed at least one strut and at least 3 cables connected. Hence, considering N number of strut as input in the script, the process generated 2N number of symmetric nodes divided in 2 planes (each plane with N nodes) in a circular equidistant manner. These nodes are then randomly connected by 4N number of links such that each node has 4 set of links. These links are then randomly assigned component properties with the limitation of each node bearing one strut and 3 cables. The struts and cables are now randomly exchanged and shuffled without changing the limitation of number of struts and cables at each node but producing variant basic (unstable) seed morphology.

The next step of dynamic relaxation of the unstable basic seed required assigning elastic modulus to the cables. The cables (3N) are divided into form-finding elastic cables (coded blue in diagram) and non-form-finding cables (coloured black in diagram). The form-finding cables were the links connecting nodes vertically and non-form-finding cables connected the nodes horizontally in same plane. This was followed by selecting randomly set of 3 nodes and fixing these nodes in x-y-z planes, y-z planes and z plane respectively, thus fixing 6 degrees of freedom in translational motion (Tibert and Pellegrino, 2003). The basic seed was then relaxed using Rhino-membrane plug-in interface.

In order to further compare and evaluate the produced geometries, each of the resultant morphologies was digitally tested for respective spatial properties of enclosed volume, base area and clear height. The reason to have a geometric evaluative analysis of the vastly variant relaxed morphologies produced was to eliminate the “architecturally” unusable forms, as this is an investigation to produce forms that would prove useful to be inhabitable spaces. This indicated that larger unobstructed volumes (with higher clear height) and morphologies with larger base

area (and hence more stability) were potentially fitter for architectural applications. An algorithmic script was written to calculate these properties of volume, base area and clear height to the closest plausible values, as precise calculation was not only tedious but computationally time-consuming. For volume calculation, bounding boxes enclosing the geometry were generated where each bounding box was aligned with each one of the outer plane of the geometry. (Alternately the convex hull method could also have been used to calculate the volume of the morphology.) The minimum volume of the bounding box was chosen as the geometry volume. Same concept was used to algorithmically calculate base area (by selecting maximum of the various 3-point planar areas) and clear height (by choosing least of the internal 1 point to 3 points planar distances). In terms of the weightage of the above geometric fitness criteria, the enclosed volume was the most important (for spatial usability), followed by larger base area (for stability) and then finally the clear height. Thus the morphology with highest volume would tend to be fittest, with its largest base area being used to help achieve the most stable orientation and larger ground space for habitation and enclosure, and preferably the most plausible clear height to provide enough room internally for optimal spatial usage.

2.2. MORPHOLOGY GENERATION

Using the generative script, at least 40 unstable basic seeds were created with 5 struts, 6 struts, 7 struts, 8 struts and 9 struts geometries (since 3 and 4 strut geometries produced only 1 and 2 seeds respectively). Each of unstable basic geometries had unique connection logic, and thus would produce high variation in their respective relaxed modules. It was observed that 6 and 8 struts geometries had a tendency to relax into similar relaxed geometries and produce less variation while odd numbered strut geometries like 5, 7 and 9 struts produced more variant relaxed geometries. Also the number of form-finding and non form-finding cables played a crucial role in stability of geometries. It was observed that geometries with higher ratio of number of form-finding cables and number of vertical struts produced lesser number of stable geometries.

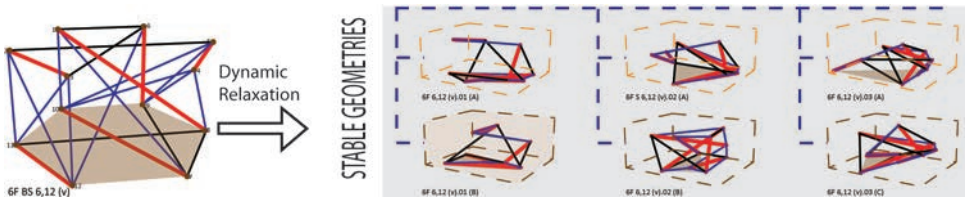

Figure 2. A six strut unstable basic seed resulting in multiple stable geometries.

2.3. EVALUATION STAGE 1- VOLUMETRIC PROPERTIES

Once calculated, each of the respective geometric data was graphically plotted as shown in the example in order to have a comparative analysis and elimination procedure. The geometries with maximum enclosed volume, larger base area and higher clear heights were selected thus eliminating the flatter, condensed and contracted unusable geometries.

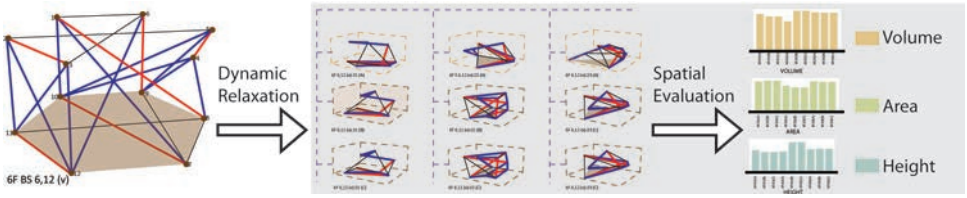

Figure 3. Volumetric evaluation a six strut basic seed and the corresponding geometries.

2.4. EVALUATION STAGE 2-FABRICATION EASE

The second stage of evaluation intended to access the fabrication ease of the modules. The first step involved eliminating geometries with intersecting struts as it was structurally not feasible to fabricate, while the second step involved analysing uniformity in the strut and cable lengths for fabrication ease. In order to assess this regularity in lengths of struts and cables, values for each strut and cable length is plotted graphically. A flatter line graph implied higher uniformity in component dimensions. This procedure helped in retaining economically buildable modules and eliminated geometries with too many varying strut and cable lengths. The filtered out modules were then selected for further structural tests and analysis.

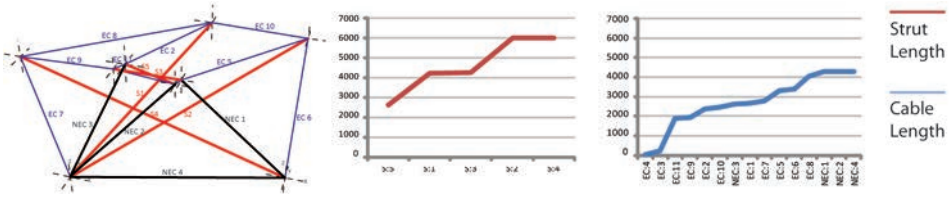

Figure 4. Graphical representation of strut and cable lengths a selected geometry.

2.5. STRUCTURAL TESTS

Structural analysis in Strand was carried out for the selected modules to simulate the deflection of the nodes and the buckling threshold of the struts under the assigned load and to get the appropriate geometry of the components.

For the digital setup, struts were assigned properties as beams with elastic modulus. Cables were defined as springs with axial stiffness of each cable inversely proportion to its length. Based on the geometry, minimum three nodes were fixed on the ground in the translational x, y and z axis keeping the rotational movement free. The other nodes were subjected to a load of 1000 N in the (-z) direction. Each module was tested for three strut cross-section diameter value viz. 20mm, 50mm and 75mm and under three load cases with varying pretension values of 0.02, 0.01 and 0.001 in the tension cables.

2.5.1. Linear static analysis

LSA was carried out to study the deflection in the geometry caused due to the designed load. Based on the inferences of the above experiments, the final strut geometry and cable pretension value was decided. In certain cases to get the desired stability for the designed load, combinations of different strut dimensions was explored. This exercise helped in classifying the geometries based on their structural stability and load bearing capacity.

2.5.2. Linear buckling analysis

The LBA estimated the load at which the struts will begin to buckle and was governed by the strut diameters. The structural analysis done for one of the selected modules is shown below where the buckling loads for the structure was calculated. Since the buckling load was lower than the required design load the struts had to be redesigned by changing the diameter in order to increase the strength of the structure and to ensure stability under critical load of 1000N.

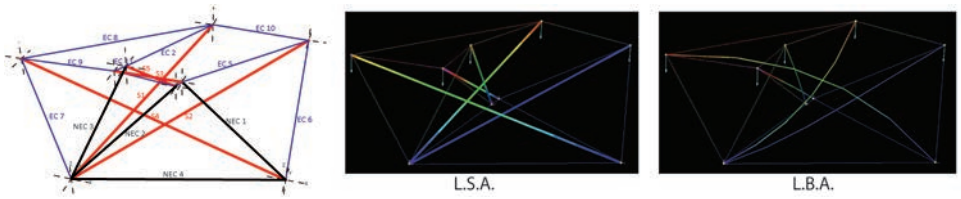

Figure 5. A selected geometry tested for Linear Static and Buckling Analyses.

3. Dynamic Experiment

3.1. MULTIPLICITY

The next step of the experiment was to test the selected modules for possibility of dynamic spatial re-configuration. The strut and cable dimensions and lengths play a very crucial role in the stable configuration of the relaxed form. This property of producing variant stable forms with slight change in the dimension was used to achieve dynamism in the form by manipulating component lengths and orientation. This experiment was carried out to test each of the selected design modules for possibility of distinctly usable spatially reconfigured organization. This characteristic feature was the key to achieving program based dynamic performance of the system.

The manipulation of the component properties was carried out by either changing the length of struts or the rotating the struts with one fixed end. The experiment was limited to manipulating only one strut at a time; only the 3 struts with one end fixed at the base were manipulated. The length change was limited to either increasing or decreasing by 1.5 m at the free end of the fixed strut. The change would be achieved by having telescopic struts that could be increased and decreased by 1.5 m at the free end of each of the 3 fixed struts. The telescopic change would require to be triggered manually as per the programmatic need or user need to reconfigure the structure for enclosed space. However, due to pre-stressed nature of the system, this mechanism would require either use of motors or dismantling of structure and re-assembly of the module.

The rotational change was also limited to a + 100 or – 100 in the x-y plane about the fixed end of the strut. The change would be achieved by using pin jointed detailing with freedom for rotation at the fixed end. The digital experimentation was carried out in Rhino-membrane by re-assigning the component properties and relaxing the structure again after the manipulation. In both the cases the module sometimes produced a large spatial variation and re-configuration, but most of the times resulted in swaying.

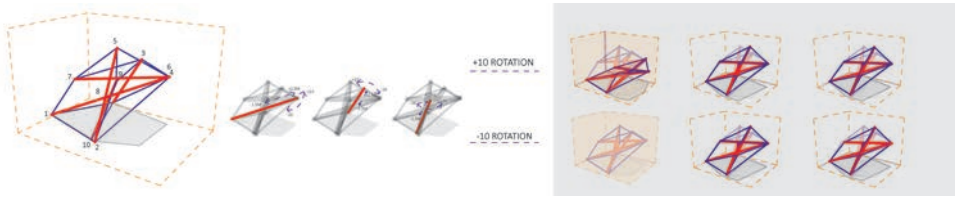

Figure 6. Selected module tested for rotational manipulation of component.

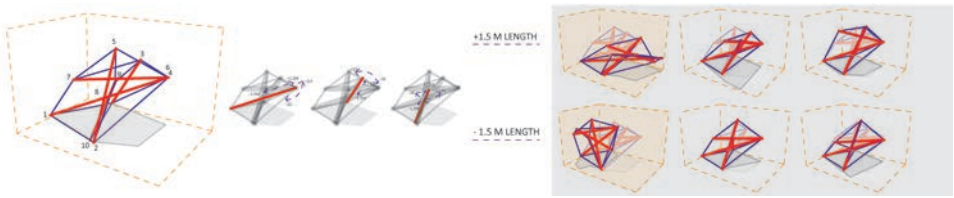

Figure 7. Selected module tested for length manipulation of component.

3.2. MEMBRANES

The next design step was creating enclosures in these design modules by not only retaining the spatial differentiation of spaces but rather enhancing it using tensile membranes. In order to understand the structural implications of the membrane addition, the modules were again tested under same conditions as before for structural stability. It was observed that the tensile membranes affected the buckling loads as the structure had now started failing at lower threshold loads implying that the strength of the structure required to be regained by further increasing the strut diameter.

Figure 8. Linear Buckling Analysis Test on module after membrane addition.

4. Conclusion

The use of digital scripting tools to predict structural behaviour and formulate the algorithmic form-finding process helped in exploring the vast design space domain of irregular tensegrity structures which has been very sparsely explored. The intense evaluation stages and elimination process helped in efficiently filtering out the potentially usable design modules. Simulation of non-linear complex system behaviour and the multiple-stable states of morphologies, produced from the generative process, provided an efficient digital apparatus for further studying, analysing irregular tensegrity structures including its varied application possibilities.

Figure 9. Modular reorganisation to form architecturally habitable and re-configurable spaces and structures.

However, there is a need of a feed-back loop in the digital exploration which would enable the learning and conclusions of each stage to be applied in the process by re-iterating the stages with revised procedures.

Combining the system with springs or sensors would further investigate the dynamic system behaviour without the need to mechanically change the structure. There is also further scope of researching on methods and techniques that would explore the modularity of the system in much deeper sense to come up with more emerging complex structural systems.

References

DeLanda, M.: 2004, Material Complexity, in N. Leach, D. Turnbull and C. Williams (eds.), *Digital Tectonics*, Wiley-Academy

Ingber, D. E.: 2003, Tensegrity I. Cell structure and hierarchical systems biology, *Journal of Cell Science*, **116**(7), 1157–1173.

Leach, N: 2004, Swarm Tectonics, *in* N. Leach, D. Turnbull and C. Williams (eds.), *Digital Tectonics*, Wiley-Academy.

Paul, C., Lipson, H. and Cuevas, F. J. V.: 2005, Evolutionary form-finding of tensegrity structures, *Proceedings of the 2005 conference on Genetic and evolutionary computation – GECCO '05*.

Peitgen, H.-O., Jurgens, H. and Saupe, D.: 1992, *Chaos and Fractals: New Frontiers of Science*, Springer.

Tibert, A. G. and Pellegrino, S.: 2003, Review of Form-Finding Methods for Tensegrity Structures, *International Journal of Space Structures*, **18**(4), 209–223.

Williamson, D., Skelton, R.E. and Han, J.: 2002, Equilibrium Conditions of a Tensegrity Structure, *Proceedings of the Third World Conference on Structural Control (*3WCSC*)*, 7–12 April 2002, Como, Italy.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 107–116. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

BIO-INSPIRED ADAPTIVE STADIUM FAÇADES

An evolution-based design exploration

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Abstract. Our research focuses on bio-inspired evolutionary design based on genetic algorithms to explore façade surfaces that improve adaptivity and solar performance of stadium design during the early stages of design development. This paper describes prototype implementation of an automated computer design system, its architecture, and initial results. Our approach highlights importance of early exploration of architectural geometries by rapidly narrowing down optimised design solutions within an infinite search space of possible design solutions. Additionally, the prototype supports automatic generation of design variations and demonstrates potential use of genetic algorithms as a means to constrained design exploration.

Keywords. Adaptive façades; evolutionary design; genetic algorithm; performance simulations.

1. Introduction

The development of digital design tools and corresponding techniques enable parametric design of building envelopes with a range of geometric complexity. The role of such envelopes as part of stadium designs, however, tends to be largely aesthetic or symbolic without taking passive building performance into consideration. Bio-inspired design approach, in such a case, is likely to be a promising solution not only to evaluate alternative design proposals but also to generate design solutions, attaining both sustainability and long-term adaptability as part of environmental concerns. In this regard, our research is inspired by static and dynamic adaptation processes observed in nature. Static adaptation is achieved by searching for appropriate overall forms of façade surfaces using genetic algorithms, and dynamic adaptation is achieved by designing bio-inspired reorientable components to control interior conditions. This paper focuses on evolutionary design process using

genetic algorithms (GAs) to help improve adaptivity and solar performance of stadium façade surfaces especially during the early design stages.

Although there are numerous studies that demonstrate the potential of genetic algorithms for performance-based façade designs such as Caldas and Norford (2002), Sato et al. (2002), Lauret et al. (2005), and Turrin et al. (2011), the scope of such investigations is mostly restricted to the fixed initial spatial geometry and the one main optimisation objective, namely to minimise energy consumption.

In contrast, this paper describes potential enhancement to the façade design process by performing daylight simulation at an early stage as part of an integrated computer design system based on genetic algorithms.

2. Genetic Algorithms

2.1. OVERVIEW OF GENETIC ALGORITHM

In genetic algorithms, a population of solutions for a certain problem is produced and the 'fittest' ones among them are selected for reproduction of the next generation. This process reflects the principle of natural selection. Offspring are then generated from these selected parents using variation operators such as crossover and mutation resulting in new fitter solutions.

Genetic algorithms are found to be a more efficient evolutionary generative strategy within a large and complex search space that requires less of mathematical analysis and instead uses probabilistic transition rules, not deterministic ones, even with little information about a given design problem.

2.2. GENETIC ALGORITHMS IN ARCHITECTURE

Genetic algorithms have been used in architecture to address various design objectives. Among others, structural analysis (Camp et al., 1998; Shea et al., 2005; Schein and Tessmann, 2008; El Gewely, 2010) and environmental performance (Richards, 2011; Spaeth and Menges, 2011) appear as two prime application areas in architectural design to successfully apply genetic algorithms. In such applications, optimisation algorithms are often coupled with performance models and simulation techniques to generate optimal or acceptable and approximate spatial configurations for design problems.

3. Prototype

3.1. GENERIC STADIUM FAÇADE MODEL

The particular building type used as an illustrative case for this research is a stadium. The evolutionary design strategy in the prototype is used to generate

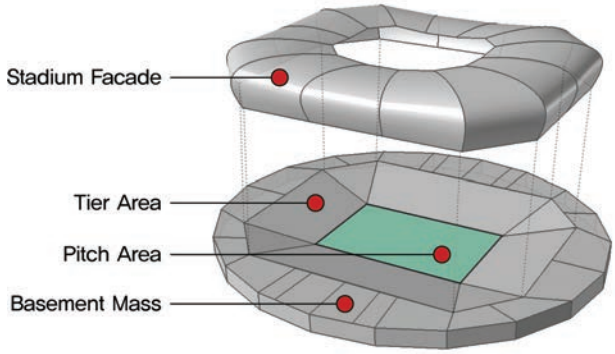

Figure 1. Generic 3D model composition of a stadium.

stadium façades, comprising peripheral and roof surfaces. The prototype system includes a variety of design information such as geometric parameters, formal constraints, and environmental data. The integrated use of such information provides a powerful design environment that explores many design alternatives quickly, thus resulting in a better design solution.

To identify appropriate knowledge about primary composition of a stadium and to improve efficiency of environmental performance, a generic three dimensional model is defined with four building elements: stadium façade, tier area, pitch area, and basement mass, as shown in Figure 1.

The geometry of stadium façades is defined by a lofted surface with profile curves generated with four variables (Figure 2). To avoid geometric inconsistency which may be caused by extreme values, control variables that define profile

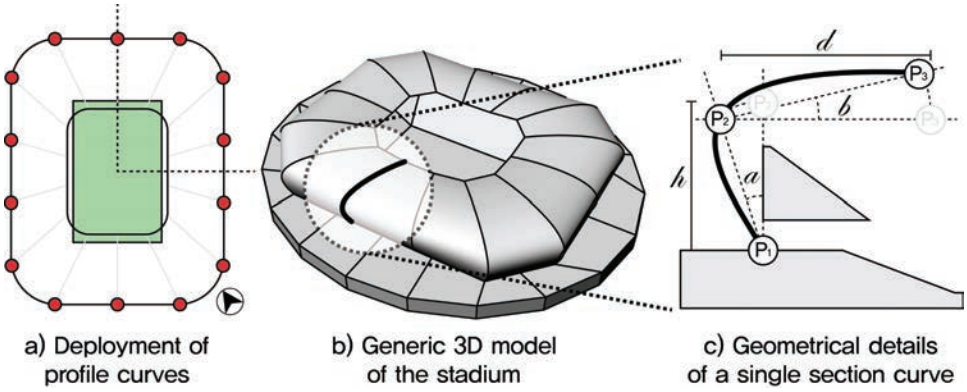

Figure 2. Definition of stadium façades with profile curves and key variables.

Table 1. Discrete control variables for profile curves.

Variable	Variable Type	Nominal Value	Range	Possibilities
Height of façade elevation	Integer	25m	$25\text{m} \le h \le 35\text{m}$	11
Tilting angle	Integer	20°	$0° \le a \le 30°$	31
Roof coverage	Integer	60%	$10\% \le d \le 100\%$	91
Inclination angle	Integer	10°	$-10° \le b \le 10°$	21

curves are constrained within the range of a given domain. Each variable has a different discrete range of values and number of possibilities to increase the probability of generating varying populations as listed in Table 1.

3.2. SIMULATION PARAMETERS

Daylighting is one of the major environmental issues heavily dependent on the orientation, the shape and the material properties of stadium façades. According to the technical recommendations and requirements of FIFA (Fédération Internationale de Football Association), spectators must be protected as much as possible from the glare of the sun whereas it is critical that there is a reasonable amount of direct sunlight in as many sides of the playing field as possible.

In our research, two daylight values are evaluated once a genetic algorithm generates a population of different façade surfaces: direct solar radiation values on both pitch and tier areas (Wh/m^2) and percentage of pitch area exposed to the sunlight (%) for a given time duration. During the simulation, these values are collected from the reference points on the analysis grid located on the surface of these two areas. The integrated use of these two values is expected to improve objectivity and accuracy of output fitness values and to avoid possible bias that may arise with use of only one type of variable. Material properties of roof and its implication on diffuse radiation, however, are not within the scope of this research. Details and implementations of each variable are discussed in the fitness function section (Section 4.3).

4. Implementation of Genetic Algorithm

4.1. SYSTEM IMPLEMENTATION

As shown in Figure 3, the system proceeds by initialising three dimensional model data with specific environmental conditions based on information for the given site.

Once all required initial data are specified for genetic algorithm operations, possible solutions under the given conditions are populated with control genes

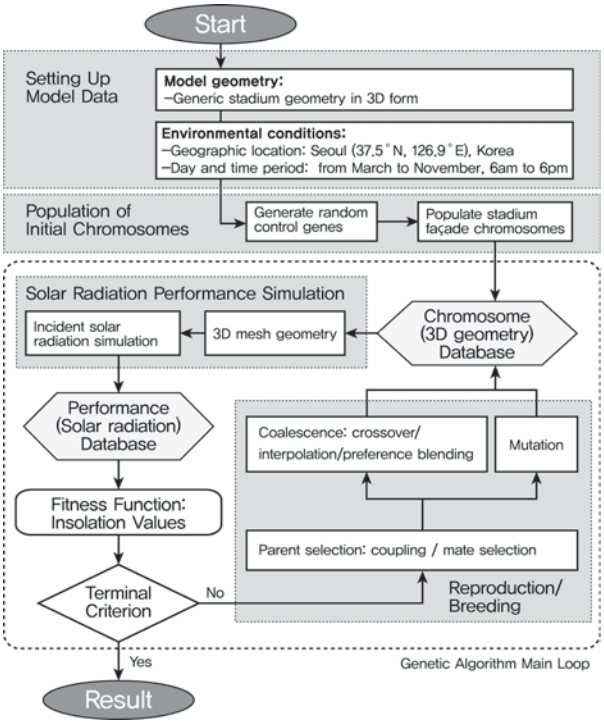

Figure 3. Evolutionary design system flow chart.

selected randomly from the control pool. Next, three-dimensional geometries of stadium façade are generated in the scene which compose the chromosome database before the performative simulation. In the evolution-based design system using genetic algorithms, the terminal criterion normally refers to either the number of generations or the specific fitness value. That is to say, once the system has populated a given number of generations converging towards a certain optimised solution, or a fittest individual that satisfies the pre-defined fitness condition is generated, further execution of genetic algorithms is halted to output desirable solutions. In our research, the terminal criterion is based on a certain number of stagnant generations in which the fittest genome has the same fitness value as the fittest genome in the previous iteration before the evolution aborts.

4.2. GENOTYPE: PROFILE CURVE

Considering different types of parameters and geometric peculiarity of stadium façade within this system, it is more appropriate to use an integer coding system

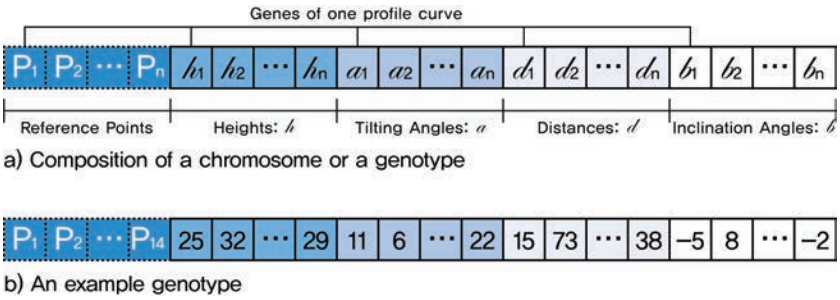

Figure 4. Genotype composition and an example.

when defining genotype of profile curves. It is also necessary to consider the length of chromosomes based on complexity of façade geometry and workflow efficiency of the whole system. Therefore, the system is set to a reasonable number of fourteen profile curves in one chromosome and each pair of five discrete genes represents one profile curve, resulting in an optimisation of geometry complexities and calculation loads (Figure 4).

4.3. FITNESS FUNCTION

Since it is desirable for the pitch area to get exposed to as much sunlight as possible and vice versa on the tier area for spectators' visual comfort, the chromosome with maximum sunlight fitness value of F is the fittest in a population, expressed in a discrete function as:

$$F = avgP_{\text{sol}} - avgT_{\text{sol}} + avgP_{\text{exp}} \tag{1}$$

where F is the sunlight fitness value, avgPsol and avgTsol are the daily average values of direct solar radiation (Wh/m^2) on the pitch and the tier area respectively, and $avgP_{\text{exp}}$ is the daily average percentage of the solar exposure of the pitch area.

Considering the input variables and their relationships inside the fitness function, however, there are two issues need to be addressed. Firstly, Equation (1) should not be a linear function. In other words, making a bright area of the pitch even brighter should not be treated the same as making a shaded part bright. Secondly, all variables should not be treated equally due to the fact that they do not have the same units.

To deal with the first problem, a weighting should be given to each variable according to its implication for the outcomes. The most obvious one is to assign

either an incremental or a decremental penalty clause to each variable to make the relationship between the solar radiation and the fitness value as follows:

As shown in Figure 5, Δs denotes a change in solar radiation value of the pitch area and Δf the corresponding change in fitness. The most well-known and reliable operator that can give the above relationship is the square root. By assigning the square root to each variable, a specific loss of solar radiation and solar exposure results in a much heavier fitness penalty when there is less sunlight onto the pitch area. Equation (1) is now tuned as follows:

$$F = sqrt(avgP_{sol}) - sqrt(avgT_{sol}) + sqrt(avgP_{exp}) \quad (2)$$

Equation (2), however, still needs to be refined regarding the second issue of disparate units of variables involved. This issue can be solved by introducing factors into the fitness function to pull the variables into the same range of values. For example, $avgP_{sol}$ and $avgT_{sol}$ are values ranging approximately from 100 Wh/m^2 to 1400 Wh/m^2 whereas the value of $avgP_{exp}$ ranges only from 10% to 90%, approximately. This means that even the bigger change in solar exposure will only have subtle influence over the fitness value in a given setup. This problem can be resolved by multiplying $avgP_{exp}$ values by a fudge factor of 10 in order to assign corresponding significance:

$$F = sqrt(avgP_{sol}) - sqrt(avgT_{sol}) + (10*sqrt(avgP_{exp})) \quad (3)$$

Now a change in a solar exposure has a reasonable chance of affecting the fitness score during the performance analysis. The objective of this calculation is to find genes that maximise values of $avgP_{sol}$ and $avgP_{exp}$, and minimise the values of $avgT_{sol}$, which, in return, results in the maximum value of F. This determines

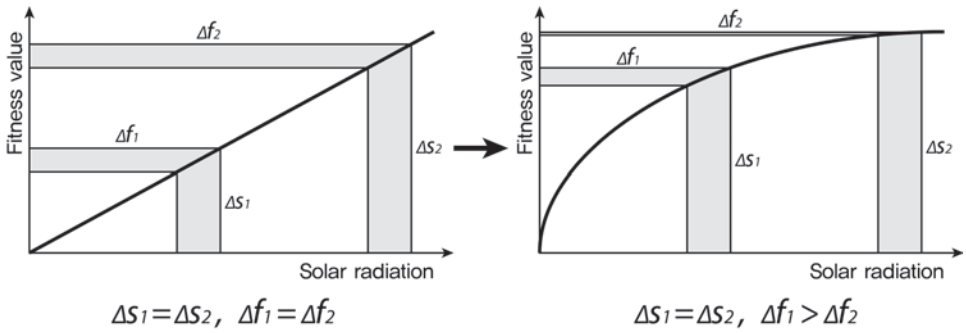

Figure 5. Penalisation of fitness function.

the raw fitness of each individual in the population and is used to determine the rank order.

5. Simulation Results

In the initial population of the first generation, the parameters of the profile curves are chosen randomly from the available pre-determined ranges based on the restrictions or preferences indicated by the user. The genetic algorithm parameters are: population size = 20, and number of stagnant generations = 20. Additionally, a combination of elite selection and roulette selection is used. Five percentages of the fittest individuals from the previous population are carried over to a new generation, and the rest are selected by the roulette selection mechanism.

The implemented genetic algorithm investigated a variety of façade surface geometries over 60 generations converging to the fittest design solution (Figure 6). The range of geometric possibilities was explored in terms of sunlight levels. In the optimised solution, the fitness scores were kept to the maximum, which means that solar radiation and exposure values on the pitch area are maximised and vice versa on the tier area.

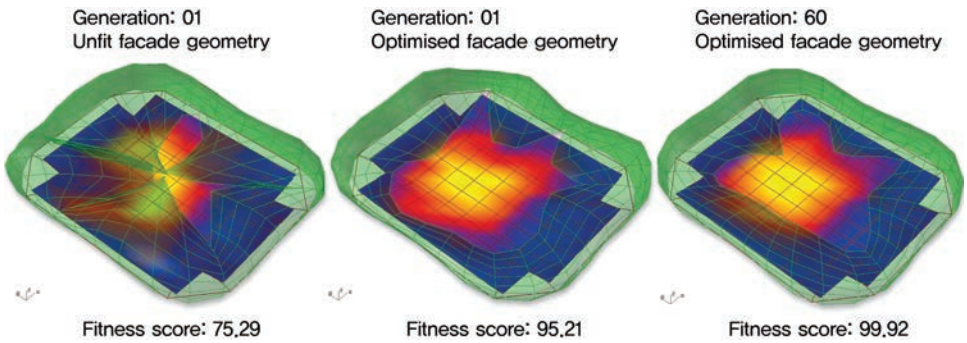

Figure 6. Unfit and optimised façade geometries after 60 generations.

Figure 7 and Table 2 show the overall results of performance analysis over 60 generations. Although there is a considerable variation of façade geometries in the initial stages, the optimised solutions or the best individuals converge to a certain form with slight differences in the genes over the generations. This restriction can be relaxed by varying values of the elite percentage which leads to a larger number of possible design alternatives.

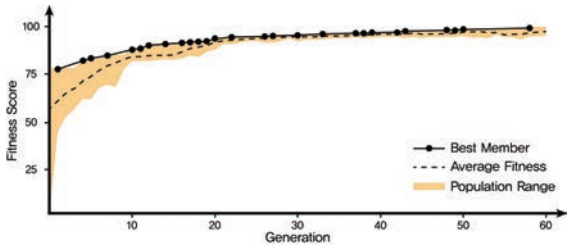

Figure 7. Population graph of best and average individuals over 60 generations.

Table 2. Best fitness score over 60 generations.

Generation	**10**	**20**	**30**	**40**	**50**	**60**
Best Fitness Score	97.62	97.86	98.38	98.86	99.56	99.92

6. Conclusions

This paper has presented an illustrative study of stadium façade design system based on genetic algorithms. Such an approach is powerful because, unlike conventional top-down search methods, it explores an infinite search space of possible design scenarios within a pre-defined range towards convergent optimised design solutions, responding to specific performance criteria. Additionally, it provides an automatic generation of geometric variations which can expand search for a range of other design solutions. In order to further develop this approach, it is necessary to comprehend the required parameters and their relationships from the contextual viewpoints, which is a key challenge for integration of genetic algorithms in architectural design.

GA-based design approaches still have some drawbacks. Firstly, there is a lack of consistency in the final solutions due to the randomly generated initial parents that determine subsequent offspring. Of course, this can be improved by increasing the number of initial populations and running many generations, but it can cost additional time and reduce efficiency of the overall process. Another limitation is the tendency for a local optimum to happen during the evolutionary process. Keeping in mind the purposes of performance-based design approach, systems such as the one presented here are best used as means to assist designers with alternative designs and not to recommend any one global optimum as a final solution.

The next phase of this research is planned to take one step further and explore how to subdivide surface geometries into reorientable components for dynamic responsiveness.

References

Caldas, L. G. and Norford, L. K.: 2002, A design optimization tool based on a genetic algorithm, *Automation in Construction*, **11**(2), 173–184.

Camp, C., Pezeshk, S. and Cao, G.: 1998, Optimized Design of Two-Dimensional Structures Using a Genetic Algorithm, *Journal of Structural Engineering*, **124**(5), 551–559.

El Gewely, M. H.: 2010, Algorithm Aided Architectural Design (AAAD), *Proceedings of the 5th ASCAAD Conference*, Fez, 117–126.

FIFA (Fédération Internationale de Football Association): 2011, "Football Stadiums: Technical Recommendations and Requirements 5th ed.". Available from: Open Source Repository http://www.fifa.com (accessed 5 February 2013).

Holland, J.: 1973, Genetic Algorithms and the Optimal Allocation of Trials, *SIAM Journal on Computing*, **2**(2), 88–105.

Lauret, P., Boyer, H., Riviere, C. and Bastide, A.: 2005, A Genetic Algorithm Applied to the Validation of Building Thermal Models, *Energy and Buildings*, **37**(8), 858–866.

Richards, D.: 2011, Towards Morphogenetic Assemblies: Evolving Performance Within Component-Based Structures, *CAADRIA2011*, New Castle, 515–524.

Sato, S., Otori, K., Takizawa, A., Sakai, H., Ando, Y. and Kawamura, H.: 2002, Applying Genetic Algorithms to the Optimum Design of a Concert Hall, *Journal of Sound and Vibration*, **258**(3), 517–526.

Schein, M. and Tessmann, O.: 2008, Structural Analysis as Driver in Surface-Based Design Approaches, *International Journal of Architectural Computing*, **6**(1), 19–39.

Shea, K., Aish, R., and Gourtovaia, M.: 2005, Towards Integrated Performance-Driven Generative Design Tools, *Automation in Construction*, **14**, 253–264.

Spaeth, A. B. and Menges, A.: 2011, Performative Design for Spatial Acoustics: Concept for an Evolutionary Design Algorithm Based on Acoustics as Design Driver, *Proceedings of the 29th eCAADe Conference*, Ljubljana, 461–468.

Turrin, M., von Buelow, P. and Stouffs, R.: 2011, Design Explorations of Performance Driven Geometry in Architectural Design Using Parametric Modeling and Genetic Algorithms, *Advanced Engineering Informatics*, **25**(4), 656–675.

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A DESIGN METHOD FOR MULTICRITERIA OPTIMISATION OF LOW EXERGY ARCHITECTURE

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Abstract. This paper proposes a design method for the exploration of holistic low exergy design strategies which factor in limitations and constraints of both passive and active systems. A design method that consists of a two loop structure is proposed. The inner loop consists of an automated workflow that includes three main components: a developmental procedure for generating design variants; evaluation procedures for evaluating design variants; and an optimisation procedure for optimising populations of design variants. The outer loop consists of a manual workflow that has two main components: a schema formulation process for defining the inputs to the automated workflow and a data analysis process for analysing the data produced by the automated workflow. A case study is presented that demonstrates the proposed method.

Keywords. Low exergy design; parametric design; evolutionary design; integrated design process; performance driven design.

1. Introduction

The growing concern over environmental issues such as global warming has increase the importance of energy efficient building. The current approach in architecture design mainly concentrates on optimising passive systems. However, by just focusing on passive systems it limits the potential to achieve high performance

low energy design (Ritter and Meggers, 2010). Thus a more holistic approach needs to be adopted that includes both the passive and active systems.

The concept of exergy describes both the quality and quantity of an energy source. In the tropics, the exergy of "cold" is applied in the cooling of buildings (Jansen and Woudstra, 2010). This requires the architect to look into temperatures in a design scenario to assess the appropriate exergy needed. One of the low exergy strategies appropriate for the tropics is the separation of sensible and latent cooling. However, there are limitations and constraints for implementing this strategy; the sensible heat load needs to be within the cooling capacity of the high temperature cooling systems used and systems like radiant panels will require sufficient surface area for the cooling down the space. (Chen et al., 2012b).

Thus, it is important to start considering such limitations and constraints in the early architectural design stage when alteration can still be easily made.

This paper proposes a design method for architects to explore low exergy design in the early design stage. The proposed design method combines integrated optimisation system such as GENE_ARCH (Caldas, 2006), ParaGen (Turrin et al., 2011) and DEXEN (Janssen et al., 2011) with low exergy design evaluation tools such as the DPV (Schlueter and Thesseling, 2008).

2. Integrated Design Method

The design method has a two loop structure consisting of an inner loop and the outer loop. The inner loop is an automated loop consisting of three procedures: developmental, evaluation and optimisation procedures. The outer loop is a semi-automated loop with two main components the schema formulation process and the data analysis process. The outer loop enables the architect to interact with the inner loop. The method is as follows:

1. Low exergy approach – Specific strategies appropriate to the tropical climate are selected. These strategies will affect how a design is formulated, developed, evaluated and optimised. The design project will also have an influence on the possible low exergy strategies that can be employed.
2. Outer loop
   2.1. Schema formulation process – Architects develop design base on the usual requirements of a project and with influence from low exergy strategies. The design will be parameterised into a design schema. A design schema encapsulates the design intention of the architect. It includes the generative concept for the developmental procedure and the evaluative concept behind the evaluation procedures.
   2.2. Data analysis process – Architects visualise the performance of the design variants generated from the inner loop.

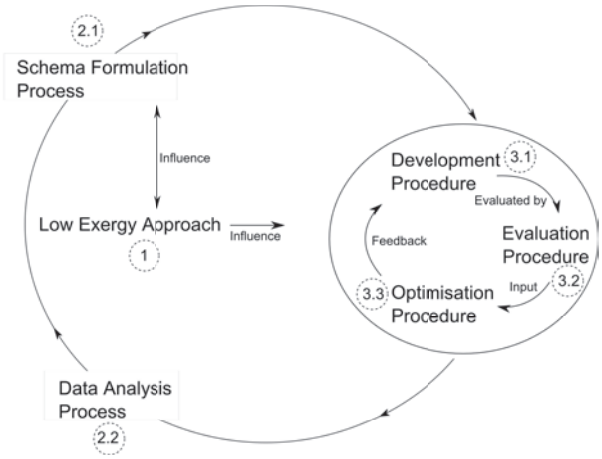

Figure 1. Integrated design method.

3. Inner loop
   3.1. Developmental procedure – Models of design variants are generated using the parametric model.
   3.2. Evaluation procedure – Models of design variants are evaluated according to various performance criteria specific to the design project.
   3.3. Optimisation procedure – An optimisation algorithm is used in order to generate better design variants.

The two loop structure ensures there is an active exchange of information between the design method and the architect. This allows the designer to escape the limits of search space imposed by a specific design schema. Information generated from the inner loop feedback into the outer loop and it will help the architect to redesign his schema. This results in a two loop iterative design process.

An architect will start a design with the schema formulation process, while in parallel considering appropriate low exergy strategies. The selected low exergy strategies will directly affect the schema and the development, evaluation and the optimisation procedures. The schema is then input into the inner loop, where design variants are optimised through an iterative process. Selected design variants are then output to the data analysis process. Based on this data analysis, the architect will gain insights on how the design schema can be improved. Once the schema has been redesigned, the inner loop can be repeated.

Each procedure is manifested into a series of workflow by using scientific workflow management tool. This facilitates the implementation of the design

method in a design scenario (Chen et al., 2012a). In the following, the design schema and the proposed method are described in detail.

3. Demonstration

A case study is presented that demonstrates the proposed method. The design schema is loosely based on the Bumps Beijing project (ArchDaily, 2009) (Figure 2). The design consists of a set of prefabricated rectangular modules stack on top of each other in a grid formation. Each module, measuring 8x24x6 metres, is two floors high. The modules are offset from one another, thereby generating overhangs and insets. For the demonstration, the design is placed in the Singapore climate.

Each module is treated as a separate zone. An exemplary low exergy strategy, the separation of latent and sensible cooling and the decentralisation of the cooling systems is used. These strategies allow each zone to have control over its own cooling system. Depending on the position, window wall ratio (WWR) and orientation of the zone, its cooling load will differ. In each zone the supply temperature for the radiant panels can be varied to meet the cooling load. The needed cooling rate is dependent on equation 1(ASHRAE, 2008).

$$\text{Cooling rate } (W/m^2) = \text{Cooling load (Watts)}/\text{Cooling surface area } (m^2) \quad (1)$$

Based on the size of the module, the amount of available cooling surface area is assumed to be constant at $307m^2$. The supply temperature is related to the cooling rate, where 18°C provide about $50W/m^2$ of cooling (ASHRAE, 2008). The Coefficient of Performance (COP) of the chiller could be optimise for the specific cooling load of each zone and thus reduce the overall energy consumption of the project according to equation 2.

$$COP_{real} = g \times (T_{hot}/(T_{hot} - T_{cold})) \quad (2)$$

where g is the carnot factor, T_{hot} and T_{cold} is the reference rejection and supply temperature respectively.

3.1. DEVELOPMENT PROCEDURE

The parametric model is constructed using SideFX Houdini 3D as follows:

a. The schema is an abstraction of the Bumps Beijing project.
b. The 8m x 24m x 6m module

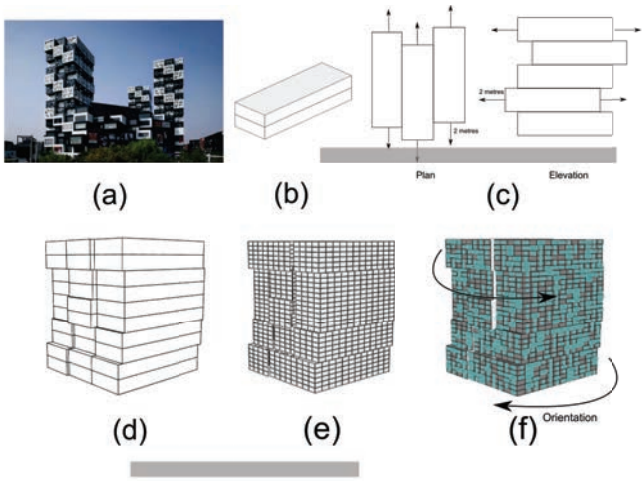

Figure 2. Design schema.

c. The positions of modules are place as shown. On the plan view they could slide along each other with a maximum limitation of two metre.
d. The modules are stacked to create the overall 3d massing.
e. A grid of 2m x 1.5m is overlaid of the façade
f. Each 2mx1.5m grid is assigned a window parameter. It has four window options and one no window option. Each window option has different dimensions and as a result will affect the WWR thus affecting the daylighting and cooling energy consumption of the building. Each window is also assigned a material parameter with a cost factor; the better insulated materials are assigned a higher cost. Finally, the building is orientated in a particular direction.

3.2. EVALUATION PROCEDURES

There are four evaluation procedures; cooling energy consumption, cost factor, daylighting and solar potential.

- Cooling energy consumption – The procedure first checks if the cooling load of each module is within the radiant cooling capacity. If the cooling load of the module is within the radiant cooling capacity, then a radiant cooling system is used. Otherwise, a conventional cooling system is used. The cooling energy consumption of the building is then calculated. The cooling energy consumption is to be minimised in the optimisation procedure.
- Cost factor – The cost factor of the building is calculated according to the different materials and the cooling systems used. The implementation cost of the low exergy

strategy is two times higher than the conventional cooling method. The cost factor is to be minimised in the optimisation procedure.

- Daylighting – The floor area receiving more than 300 lux of natural daylight is calculated using Radiance lighting simulation. The simulation is conducted using an overcast sky model, which is assumed to be the worst case scenario. The daylighting is to be maximised in the optimisation procedure.
- Solar potential – The maximum possible amount of energy generated from photovoltaics (PV) is calculated assuming the external façade is cladded with PV panels. The efficiency of the PV panels is assumed to be 15%. The solar irradiation is calculated with Radiance. The solar potential is to be maximised in the optimisation procedure.

3.3. OPTIMISATION PROCEDURE

The aim of the optimisation is to find a series of solutions that balance the trade-offs between multiple conflicting performance criteria. For example, to minimise the cooling energy consumption better quality materials can be used, however this will increase the cost factor. In order to maximise the solar potential, it is best to orientate the building towards the sun, but this will increase the cooling energy consumption. In order to reduce the cooling energy consumption, the WWR can be kept low, but this will reduce the daylighting in the interior. A design decision that is good for one criterion will result in a bad performance on another criterion.

As optimising one criterion will lead to the degradation of another, an evolutionary multi criteria optimisation is performed. The Evolutionary Algorithm (EA) can be used to effectively explore populations of design variants based on a specific design schema (Janssen, 2004). In order to compare design variants with multiple performance criteria, multi criteria EA typically uses Pareto ranking. This technique ranks design variants according to the concept of dominance. If design variant x performs better than design variant y in one criterion but perform as good in the other criteria, it is said that design variant y is dominated by design variant x. For the case study, an EA was used as follows:

1. A population of 100design variants are randomly generated by assigning random parameter values to the parametric model.
2. Each design variant is evaluated and assigned a score for each evaluation criteria.
3. A sub-population of 60 design variants is randomly selected and pareto ranked according to their scores.
4. The 30 lowest ranking design variants are “killed” and 30 highest ranked design variants are reproduced, thereby generating 30 new design variants. For reproduction, standard crossover and mutation operators are used, with a mutation probability of 0.01.

5. The cycle repeats itself from step 2. After each generation the design variants will gradually become "fitter".
6. The EA cycle was stopped after 164 generations.

4. Results

The EA ran for 164 generations and a total of 5000 design variants were generated. Figure 3 gives an overview of the optimisation process and Figure 4 shows the parallel coordinate plots of the evolution process. Figure 4(b) shows the design variants on the Pareto front. This Pareto front is made up of all design variants that are non-dominated by other design variants.

Figure 5 shows design variants of high performance. Figure 5(a) shows the designs that use low exergy systems while Figure 5(b) shows the design that use the conventional cooling systems. Interestingly, all the design variants in Figure 5(a) and (b) have the same orientation facing northwest. The geometry of the design variants are similar and are optimised to maximise both daylight and solar potential. Lastly, the WWR ranges from 0.26 to 0.28.

Figure 6 shows two design variants, with the top one being a low exergy design and the bottom one being a design using conventional systems. One can see the

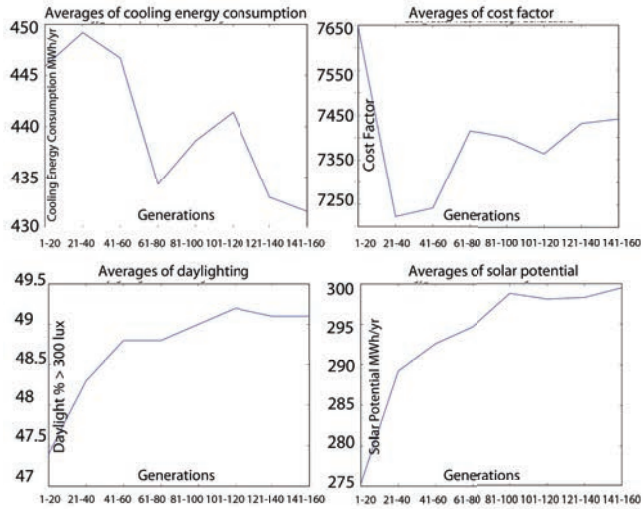

Figure 3. Averages of evaluations in interval of 20 generations.

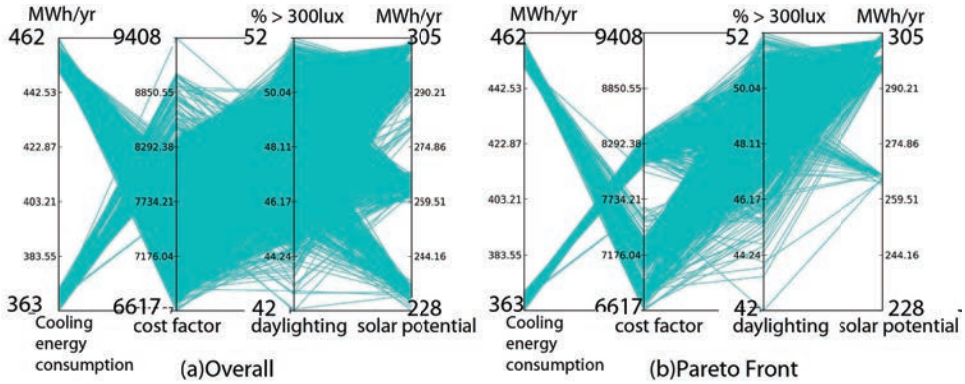

Figure 4. Parallel coordinate plots of (a) 5000 design variants, (b) Pareto front.

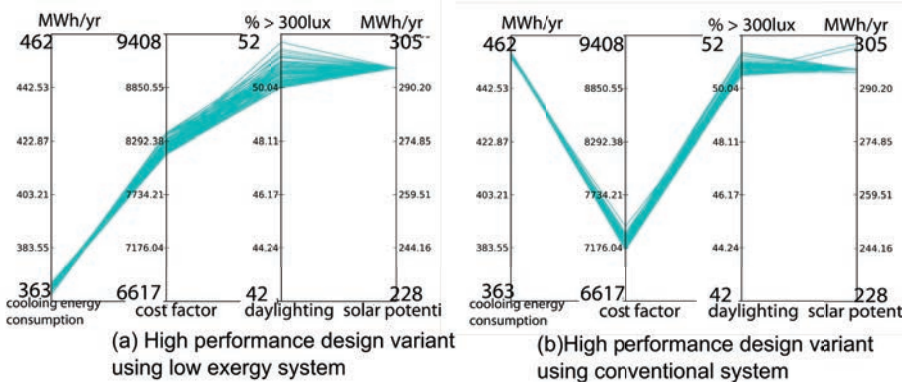

Figure 5. (a) high performance design variants using low exergy systems (b) high performance design variants using conventional systems.

similarity of the two designs in terms of the geometry, orientation and WWR. Design variant 1611 has more windows using triple low-E glass while design variant 1386 has more windows using double glaze low-E glass. For the additional material cost factor of 1177 the building could have so much more cooling energy consumption savings.

Through, the optimisation process the architect will be able to explore the alternative trade-offs between conflicting performances criteria and make more informed design decision.

This information can then be fed back to the outer loop for the next round of optimisation. For example, with information of the best orientation and WWR one

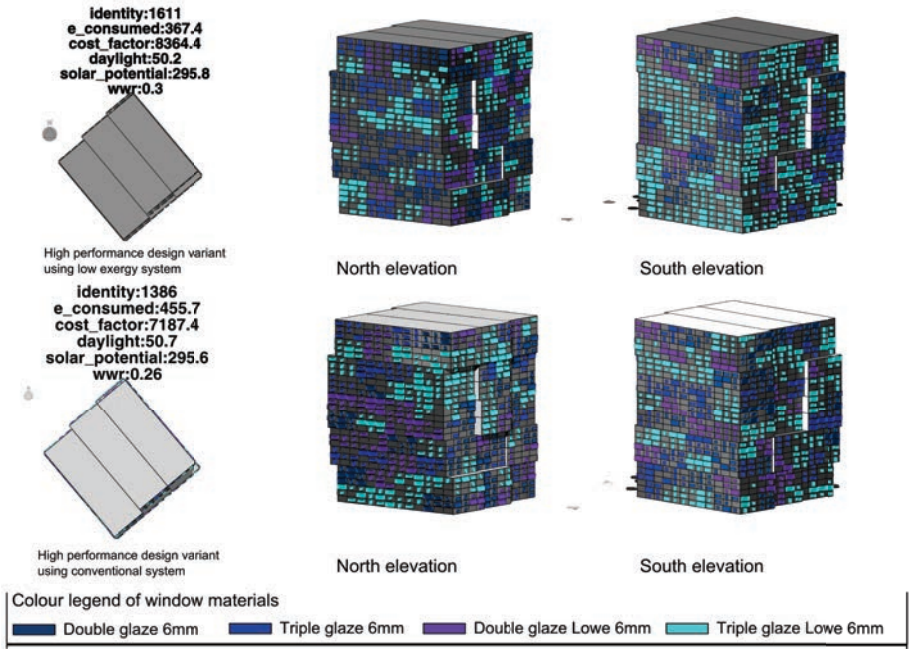

Figure 6. Top: design variant using low exergy system Bottom: design variant using conventional systems.

could narrow down the schema by removing the orientation parameter and constraining the WWR. The next round of optimisation could then focus on the exploration of improved façade design.

5. Conclusion

The optimisation process highlighted key strategies that could be used with regards to the geometry and orientation of the building. All the best performing design variants face northwest and have a similar geometry. The WWR of 0.26 to 0.28 gives a good daylighted interior while at the same time maintain the cooling load with a certain level of envelope quality.

Through analysing and generalising the results of the optimisation run, the architect can discover design strategies that consistently result in good performance. In this way, the computer becomes an active participant in the design process. This is only possible with a well-integrated design method. Further investigations will look at niching of the genetic algorithm data to give a more diverse population in the result and thus give the architect more design options.

References

ArchDaily: 2009, “Bumps/SAKO Architects”. Available from: <http://www.archdaily.com/44831/bumps-sako-architects/> (accessed 14 December 2013).

ASHRAE: 2008, *2008 ASHRAE Handbook - HVAC Systems and Equipment (SI)*, ASHRAE, Atlanta, GA.

Caldas, L.: 2006, GENE_ARCH: An Evolution-Based Generative Design System for Sustainable Architecture Intelligent Computing in Engineering and Architecture, *in* I. Smith (ed.), *Intelligent Computing in Engineering and Architecture, Lecture Notes in Computer Science* vol. 4200, Springer Berlin / Heidelberg, 109–118.

Chen, K. W., Janssen, P. and Schlueter, A.: 2012a, Performance Driven Design Optimisation with Scientific Workflow System, *Green Building Optimization Design*, Shengyang, China

Chen, K. W., Schlueter, A. and Janssen, P.: 2012b, Optimisation of low exergy architecture in the tropics, *Sustainable Future Energy 2012 and 10th SEE Forum, Innovations for Sustainable and Secure Energy*, Brunei.

Jansen, S. and Woudstra, N.: 2010, Understanding the exergy of cold: theory and practical examples, *International J. Exergy* **7**(6), 693–712.

Janssen, P.: 2004, *A design method and a computational architecture for generating and evolving building designs*, PhD dissertation, School of Design, Hong Kong Polytechnic University.

Janssen, P., Basol, C. and Chen, K. W.: 2011, Evolutionary Developmental Design for Non-Programmers, *ECAADE 2011*, Ljubljana, Slovenia, 307–314.

Ritter, V. and Meggers, F.: 2010, Assessment of the guidelines for zero-emission architectural design, *Clima 2010- 10th REHVA World Congress*, Antalya, Turkey.

Schlueter, A. and Thesseling, F.: 2008, Building information model based energy/exergy performance assessment in early design stages, *Automation in Construction*, **18**(2), 153–163.

Turrin, M., von Buelow, P. and Stouffs, R.: 2011, Design explorations of performance driven geometry in architectural design using parametric modeling and genetic algorithms, *Advanced Engineering Informatics*, **25**(4), 656–675.

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SEMI-TRANSPARENT BUILDING INTEGRATED PHOTOVOLTAIC FACADES

Maximise energy savings using evolutionary multi-objective optimisation

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Abstract. The optimisation of semi-transparent building integrated photovoltaic facades can be challenging when finding an overall balanced performance between conflicting performance criteria. This paper proposes a design optimisation method that maximises overall energy savings generated by these types of facades by simulating the combined impact of electricity generation, cooling load, and daylight autonomy. A proof-of-concept demonstration of the proposed method is presented for a typical office facade.

Keywords. Multi-objective optimisation; semi-transparent building integrated photovoltaic.

1. Introduction

With the current global emphasis on sustainable design, there is a trend to design multifunctional semi-transparent building integrated photovoltaic (BIPV) facades. Such facades use PV materials to replace conventional materials, such as glazing systems integrated with PV cells. Semi-transparent BIPV facades can provide good daylight availability, reduce the solar heat gain through the building envelope, and also have the ability to generate electricity to supplement the building's electricity consumption. It has been shown that semi-transparent BIPV facades are effective in improving energy efficiency and reducing the overall electricity consumption of a building (Fung et al., 2008; Robinson et al., 2009).

The challenge of designing semi-transparent BIPV facades is to optimise the multiple conflicting performance criteria. Unlike typical roof mounted photovoltaic systems, where performance is only focused on the amount of electricity generated, the design of semi-transparent BIPV facades has an impact on a wider

range of factors, including solar radiation and daylight penetration into the rooms in the building. To optimise the performance of such facades, optimisation systems can be used that leverage existing simulation tools for performance evaluation. However, the types of simulations that are required are often complex in their own right, and may take a significant amount of time to execute. Optimisation systems typically need to execute these simulations many times in an iterative manner and as a result, optimisation systems can have very long run times, with a single run possibly taking weeks to complete (Rutten, 2011).

In order to test the run time of an evolutionary algorithm, a base-case optimisation of a semi-transparent BIPV facade was conducted. A parametric model was created and an evolutionary algorithm was used to evolve an optimised population of designs. The evolutionary algorithm ran for almost 14 days. Such run times clearly do not align well with a designer's process of working.

This paper will propose an alternative method for the optimisation of semi-transparent BIPV facades. Section two gives an overview of the proposed method, and section three presents the results of a proof-of-concept demonstration where a semi-transparent BIPV facade is optimised. Finally, section four briefly draws conclusions and highlights avenues for further research.

2. Semi-transparent BIPV Facade Optimisation Method

The proposed method is based on a general design method developed by Janssen and Kaushik (2012). This generalised method is adapted to the design of semi-transparent BIPV facades using an evolutionary optimisation approach.

The method consists of three phases: 1) calibration, 2) optimisation, and 3) validation. In the calibration phase, simulation models are selected and simulation programs are configured and tested. Simulations that are deemed too slow are replaced by faster proxy simulations, which are configured in order to ensure that appropriate trade-offs are achieved between speed and accuracy. In the optimisation phase, the simulations are used within the iterative optimisation process in order to explore design variants with improved performance. Finally, in the validation stage, the final designs from the optimisation phase are analysed and evaluated in more detail. Any proxy simulations are now once again replaced by the slow simulations in order to verify the performance improvements.

2.1. CALIBRATION PHASE

For the calibration phase, the first step is to decide on the performance criteria that will be considered. For semi-transparent BIPV facades, a wide range of performance criteria could be included. However, for this paper, the focus will be on

maximising the total electrical energy saved by the semi-transparent BIPV facade. Such facades impact energy savings in three distinct ways: electricity generation, cooling load, and daylight savings.

- Electricity generation is the electricity produced by the PV cells in the semi-transparent BIPV facade. Maximising electricity generation will reduce external electricity consumption from the grid.
- Cooling load is the amount of electricity required to cool a room to a set temperature. Cooling load is affected by the amount of solar radiation entering through the facade. Minimising solar radiation will reduce the electricity consumption for cooling.
- Daylight savings is the amount of electricity saved by using daylight instead of artificial lighting in order to light a room to a set minimum illuminance level. The daylight savings is affected by the daylight autonomy, which is the percentage of occupied hours per year when the minimum illuminance level can be maintained in a room by daylight alone (Reinhart, 2010). Maximising daylight autonomy will also maximise daylight savings.

For each of these components, an appropriate simulation model will be chosen and tested. If the execution time of the simulation is excessively slow, a proxy simulation will then be developed that is faster to execute, but that nevertheless stills has sufficient accuracy to guide the evolutionary process.

The total electricity saved is defined by the following formula:

$$ES = EG - CL + DS \quad (1)$$

where ES is the total electricity saving (kWh.yr), EG is the electricity generated (kWh.yr), CL is the cooling load (kWh.yr), and DS is the daylight savings (kWh.yr).

2.2. OPTIMISATION PHASE

For the optimisation phase, an evolutionary algorithm will be used to evolve a population of design variants. The evolutionary algorithm consists of three key procedures: development, evaluation, and feedback.

- The development procedure will generate design variants using a parametric model. Typically, a Visual Dataflow Modelling (VDM) (Janssen and Chen, 2010) system will be used to define the parametric model. Genes in the genotype are then associated with parameters in the model.
- The evaluation procedure will evaluate design variants. In this case, the evaluation procedure will calculate the total electricity savings, which includes the electricity generation, the cooling load, and the daylight savings.

- The feedback procedure will kill design variants that perform badly and will reproduce design variants that perform well. A variety of different strategies can be used for selection and reproduction.

2.3. VALIDATION PHASE

For the validation phase, the best designs emerging from the evolutionary process are analysed and re-simulated. At this final stage, if possible the proxy simulations are discarded, and instead the more accurate but slower simulations are used. Performance characteristics of the final design variants can then be verified.

3. Demonstration

To demonstrate the feasibility of the proposed method, an experiment was conducted.

3.1. DESIGN SCENARIO

The experiment involves optimising the pattern of PV cells on a semi-transparent BIPV facade in order to maximise the total electricity savings. The PV pattern affects both the solar radiation and the daylight penetrating into the room through the glazing, and it will therefore have an impact on all three components of the electricity savings calculation: electricity generation, cooling load, and daylight savings.

A typical north oriented office space for one person occupancy with 4m (width) x 4m (depth) x 3m (height) is modelled for the experiment, as shown in Figure 1 (left). The facade is separated into 4 zones (Figure 1, left): vision glass panel A, B, C and spandrel glass panel. Each zone is independent from each other. The PV cell

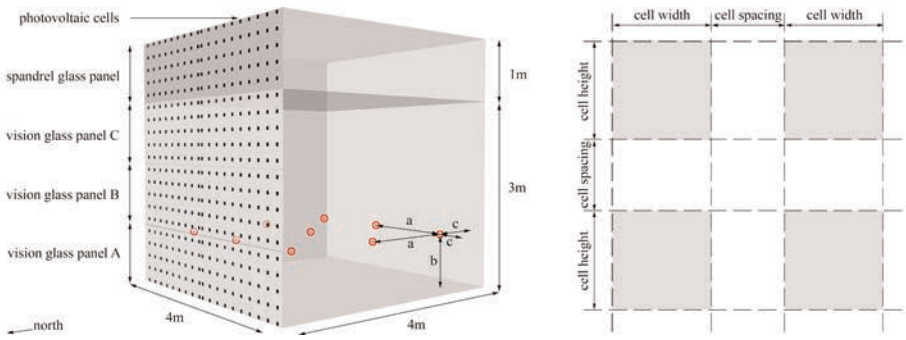

Figure 1. (left) Simulation model with sensors (a = 1.50m, b = 0.85m, c = 0.50m), (right) schematic of cell arrangement for semi-transparent BIPV façade.

pattern for each independent zone is defined by three parameters (Figure 1, right): cell height, cell width, and cell spacing. Cell height and width vary from 5 – 15.5cm at 0.5cm steps but are independent from each other. Cell spacing varies from 0.5 – 5cm at 0.5cm steps. All the cells of the semi-transparent BIPV facades will be similar in shape. The pattern occupies a facade with a height and width of 4m.

3.2. SOFTWARE TOOLS

The main tool that is used is Grasshopper (Rutten, 2011), a plugin for the Rhinocerous computer aided design modelling software (McNeel, 2010). Grasshopper (Rutten, 2011) is a VDM system that allows designers who are not trained in scripting to quickly generate parametric models. A number of specialist Grasshopper components are used for running optimisation algorithms and for executing simulations.

For running optimisations, the Galapagos component is used (Rutten, 2011). This component is an evolutionary optimisation solver which can be used to optimise designs for a single performance criterion.

For executing cooling load and daylight autonomy simulations, the DIVA component is used (Jakubiec and Reinhart, 2011). DIVA links to the EnergyPlus (Crawley et al., 2001) and Daysim (Reinhart, 2010) simulation programs.

EnergyPlus is a building performance simulation software that is based on fundamental heat balance principles. Daysim is a Radiance-based daylighting analysis tool that couples the Radiance (Ward and Shakespeare, 1998) algorithms with a daylight coefficient approach that efficiently simulates illuminance distribution in a year without executing thousands of individual ray tracing runs for all sky conditions which is impractical.

EnergyPlus is used to simulate cooling loads and Daysim is used to simulate daylight autonomy. In both cases, an EnergyPlus weather data file (NREL, 2012) for Singapore is used. The daylight autonomy is then used as a basis for calculating daylight savings.

3.3. CALIBRATION PHASE

For the calibration phase, each of the three components of the total electricity savings calculation will be considered in turn.

3.3.1. Electricity generation

The annual electricity generation of a photovoltaic module can be simulated using EnergyPlus. Ideally, it would simulate with the equivalent one-diode model

(Crawley, 2001). However, this model requires the electrical characteristic of a module to be known in advance. For an untested type of photovoltaic module, the electrical characteristic can only be obtained by fabricating the module. This poses a problem when designing semi-transparent BIPV facades with non-standard PV cell patterns, since each design option would need to be fabricated. Hence a simpler model needs to be used that is independent of the electrical characteristics. Note that the reason for using this simpler model is due to lack of input information rather than simulation speed.

EnergyPlus already has such a simple model, as an alternative to the equivalent one-diode model (EnergyPlus, 2011). In this research, we propose to use the simple model. The mathematical equation used is as follows:

$$P = A_s \times f_a \times G_t \times eff_{cell} \times eff_{invert} \quad (2)$$

where P is the electrical energy produced by photovoltaic (kWh), A_s is the net area of photovoltaic module (m^2), F_a is the fraction of surface area with active solar cells, G_t is the total annual solar radiation energy incident on PV array (which is set at 561 $kWh.m^{-2}$), eff_{cell} is the semi-transparent BIPV facades module efficiency (which is set at 12%) and eff_{invert} is the inverter efficiency (which is set at 90%).

In order to verify the accuracy of the simple model, a set of commercially produced photovoltaic modules (for which the electrical characteristics were already known) were simulated using both the equivalent one diode model and the simple model, and the results were then compared. In total, simulations for 16 different modules were carried out for the four different cardinal directions. The annual electricity generation was simulated with EnergyPlus for both models (EnergyPlus, 2011). The trend-line of 64 pairs of results for the simple and the equivalent one-diode models were plotted in Microsoft Excel. The electricity generation for the simple model resulted in an R^2 correlation of 0.98. This shows that the simple model has a good correlation and can be used in place of an equivalent one-diode model.

3.3.2. Cooling load

The cooling load for the room can also simulated using EnergyPlus. For cooling load, the study is interested in the cooling load affected by heat gain through the semi-transparent BIPV facades hence internal heat gains from lights, equipment and occupants have been set to 0. Default materials from the material library in DIVA are used. With reference to Figure 1 (left), the walls, floor and ceiling are assigned as “adiabatic” and spandrel glass panel are assigned as “opaque spandrel glass”.

A window module is defined to represent a typical 6mm thick clear glass window with U-value of 5.8, solar heat gain coefficient (SHGC) of 0.82 and visible transmittance (VT) of 0.88 (Pilkington, 2010). For the photovoltaic cells, there are two different approaches with different trade-offs between speed and accuracy. The slower more accurate approach to modelling the PV cells is to assign them as external shading elements. Each cell is assigned a solar reflectance of 0.1 and visible reflectance of 0.1. The amount of solar radiation affected by the shading from photovoltaic cells is calculated for each photovoltaic cell and for each time-step for an entire year in the simulation. Each time step calculation is different from the next because each value is dependent on the time and location of the sun. A range of 156 to 4224 photovoltaic cells with different patterns are input as external shading elements for each simulation. This large number of shading elements causes the simulation to run relatively long, with the longest simulation taking approximately 30 minutes. This caused the optimisation of the base case, mentioned in Section 1, to run for almost 14 days.

A faster proxy simulation is therefore proposed that uses a less accurate approach to the modelling of the PV cells. With this approach, the solar heat gain coefficient (SHGC) and visible light transmittance (VLT) for the facade are adjusted to take into account the effect of the PV cells. The equations for SHGC and VT used in the proxy simulation are shown below:

$$SHGC_{sst} = A_{pv}/A_{sst} \text{ x } SHGC_{st} \tag{3}$$

$$VT_{sst} = A_{pv}/A_{sst} \text{ x } VT_{st} \tag{4}$$

where $SHGC_{sst}$ is the solar heat gain coefficient of semi-transparent BIPV facade ($Wm^{-2}K^{-1}$), $SHGC_{st}$ is the solar heat gain coefficient of the vision glass panel (which is part of the semi-transparent BIPV facade) without photovoltaic cells ($Wm^{-2}K^{-1}$), VTsst is the visible transmittance of the semi-transparent BIPV facade ($Wm^{-2}K^{-1}$), VT_{st} is the visible transmittance of the vision glass panel (which is part of the semi-transparent BIPV facade) without photovoltaic cells ($Wm^{-2}K^{-1}$), A_{pv} is the area of photovoltaic cells (m^2) and A_{sst} is the area of semi-transparent BIPV facade (m^2).

In order to check the accuracy of the proposed proxy simulation, a total of 164 cooling load simulations for different BIPV facades were conducted using both the slow simulation and the proxy simulation. The trend-line for both the slow and proxy simulations were plotted in Microsoft Excel, and an R^2 correlation of 0.93 was calculated. This shows that the proposed proxy simulation for cooling load has a good correlation and can be used in place of the slower more detailed cooling load simulation.

3.3.3. Daylight Savings

Daylight savings is calculated based on the daylight autonomy for the room, which can be simulated using Daysim. Since Daysim is already an optimised simulation method (Reinhart, 2010), the simulation executed relatively quickly and there was no need to create a proxy in this case.

With reference to a recent study on various lighting standards around the world by Halonen et al. (2010), it was found that minimum illuminance for interior spaces ranges from 200lx to 500lx. Hence, for the simulation of daylight autonomy, the minimum illuminance level of 500lx is set for the simulation. Working hours are set from 9:00 to 18:00. A 3 x 3 nodal grid of daylight sensors are drawn 0.85m from the floor and 0.25m away from the vertical walls (Figure 1, left). Since daylight autonomy is more critical for areas further way from the windows, only the back 2 rows of 6 daylight sensor nodes are used for the daylight autonomy simulation.

Default materials from the material library in DIVA are used for the simulation. Based on research done by Protogeropoulos and Zachariou (2010) which shows that a typical photovoltaic module has a reflectance of below 10%, the photovoltaic layer is assigned a reflectance of 10%.

The following settings were used in DIVA/Daysim: ab = 2, ad = 1000, as = 20, ar = 300 and aa = 0.1, where ab is ambient bounce, ad is ambient resolution, ar is ambient resolution and aa is ambient accuracy. The detailed explanation of the settings is beyond this paper. They can be referred to in the Radiance manual. Daylight savings were then calculated according to the following formula:

$$DS = (DA_{sim}/100) * LPB * FA * WH \quad (5)$$

where DS is the total daylight savings ($kWh.yr^{-1}$), DA_{sim} is the simulated daylight autonomy (%), LPB is the lighting power budget ($kW.m^{-2}$), FA is the floor area of simulation model (which is $16m^2$) and WH is the working hours per year. LPB is set based on the Code of Practice (SPRING, 2006) which recommends an LPB for offices of $0.015kW.m^{-2}$. WH is set based on a 5 work days per week with 9hrs of work per day, which results in 2,340hrs per year.

3.4. ITERATION PHASE

The evolutionary solver, Galapagos, is used for the optimisation. Galapagos is executed with a population of 30, initial boost of 2%, and the maintain level is set at 10% and inbreeding at 75%. The system was executed on a single computer with an i5 Intel core CPU of 3.5GHz with 8GB of RAM, on a 64 bits Windows.

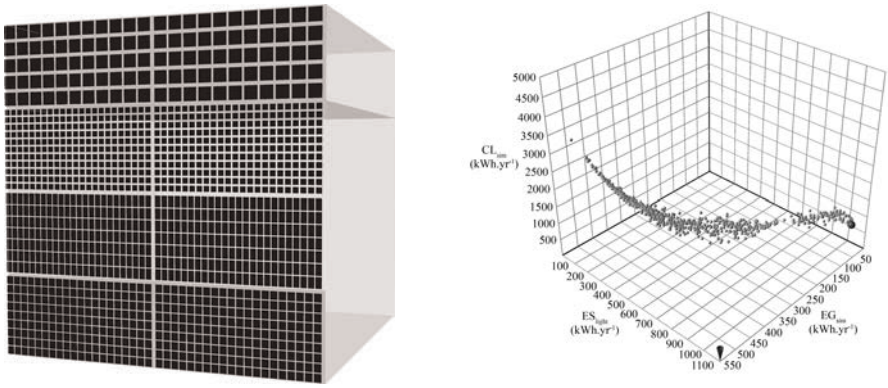

Figure 2. Optimised design.

Galapagos ran for 2 days, 17 hours. Compared to the base case which ran for almost 14 days, this method reduced the run time by 80%. The optimised design that was found at the 544th iteration is shown in Figure 2. The orange dot represents the ideal design performance and the red dot represents the design with the best performance. The fast mode optimisation process completed 1471 iterations of simulations. The optimised design is similar to the optimised design found in the base case.

3.5. VALIDATION STAGE

In the final validation phase, a set of designs from the Pareto front were selected and analysed. In order to verify the performance improvements in cooling load, these designs were re-simulated using the slow cooling load simulation. In all cases, the results from the slow mode simulation confirmed the performance improvements. In the case of the example shown in Figure 2, the optimised final design showed an overall improvement of 61% of the overall electricity over the initial design.

4. Conclusion

A design method for the multi-objective optimisation of semi-transparent BIPV facades is proposed. The overall objective is the maximisation of energy savings, but this objective embodies three distinct sub-objectives, defined as the maximisation of energy generation, the minimisation of cooling loads, and the maximisation of daylight savings. The method also significantly reduces the optimisation runtime by using a proxy simulation for calculating cooling loads.

The proposed design method simplifies the task of finding an overall balance performance for semi-transparent BIPV facades, especially where conflicting performance criteria may prove to be challenging to explore manually. This design method need not be restricted to the design of semi-transparent BIPV facades but can also be extended to optimise other design elements in a building and also include other performance criteria.

References

Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., Buhl, W. F., Huang, Y. J. and Pederson, C. O.: 2001, EnergyPlus: creating a new generation building energy simulation program, *Energy and Buildings*, **33**(4), 319–331.

EnergyPlus: 2011, *Energy: Photovoltaic*, Input-Output Reference, EnergyPlus Documentation, U.S Department of Energy, Berkeley.

Fung, T. Y. Y. and Yang, H.: 2008, Study on thermal performance of semi-transparent building-integrated photovoltaic glazings, *Energy and Buildings*, **40**(3), 341–350.

Halonen, L., Tetri, E. and Bhusal, P.: 2010, *Guidebook on Energy Efficient Electric Lighting for Buildings*, Espoo, Sweden.

Jakubiec, A. and Reinhart, C.: 2011, DIVA-FOR-RHINO 2.0: Environmental parametric modeling in Rhinoceros/Grasshopper using Radiance, Daysim and EnergyPlus, *Building Simulation 2011*, Sydney.

Janssen, P. and Kaushik, V.: 2012, Iterative Refinement through Simulation: Exploring trade-offs between speed and accuracy, *Proceedings of the 30th eCAADe Conference*, vol. 1, Faculty of Architecture, Czech Technical University in Prague, Prague, 555–563.

Janssen, P., and Chen, K. W.: 2010, Visual Dataflow Modelling: a Comparison of Three Systems, *Proceedings of the 14th International conference on Computer Aided Architectural Design*, CAAD Futures, Liège: Les Éditions de l'Université de Liège, 2011, 801–816

McNeel, R: 2010, *Rhinoceros – NURBS Modelling for Windows (version 4)*, McNeel North America, Seattle.

NREL: 2012, "Weather Data". Available from: NREL's weather data website <http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_about.cfm> (accessed 15 October 2012).

Pilkington, 2010, *Pilkington Glass Handbook 2010*, Nippon Sheet Glass, Japan.

Protogeropoulos, C. and Zachariuu, A.: 2010, Photovoltaic Module Laboratory Reflectivity Measurements and Comparison Analysis with Other Reflecting Surfaces, *25th European Photovoltaic Solar Energy Conference 2010*, Valencia, Spain.

Reinhart, C.F.: 2010, *Tutorial on the Use of Daysim Simulations for Sustainable Design*, Harvard University, Cambridge.

Robinson, L.E. and Athienitis, A.K.: 2009, Design methodology for optimisation of electricity generation and daylight utilization for facades with semi-transparent photovoltaics, *Proceedings Building Simulation*.

Rutten, D., 2011, *"Evolutionary Principles Applied to Problem Solving"*, Available from: David Rutten's blog < http://ieatbugsforbreakfast. wordpress.com/ 2011/03/04/epatps01/ > (accessed 15 October 2012).

SPRING: 2006, *Singapore Standard SS530 : 2006 – Code of Practice for Energy efficiency standard for building services and equipment*, SPRING, Singapore.

Ward, G. L. and Shakespeare, R. A.: 1998, *Rendering with Shakespeare – The Art and Science of Lighting Visualization*, Booksurge, Charleston.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 137–146. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

AN EVOLUTIONARY DESIGN PROCESS

Adaptive-iterative explorations in computational embryogenesis

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Abstract. Computational embryogenies are a special kind of genotype to phenotype mapping process widely used in explorative evolutionary systems as they provide the mechanism for generating more complex solutions. This paper focuses on how designers explore embryogenies for specific design scenarios through an adaptive-iterative process. The process is demonstrated for a complex project to generate a prototypical urban farm in Singapore. It is shown that by employing an adaptive-iterative process, the embryogeny can be made progressively more complex and less abstract, thereby allowing the exploration to be guided by the designer.

Keywords. Computational embryogeny; evolutionary; multi-criteria optimization; encoding; decoding.

1. Introduction

Evolutionary design algorithms evolve populations of designs by iteratively applying a set of procedures to design variants in the population (Frazer, 1995). With the evolutionary design approach, the parameters for a design variant are referred to as the genotype (with each individual parameter being a gene), the model of the design variant is referred to as the phenotype, and the evaluations of the design variant are referred to as performance scores. Three key procedures need to be defined: a developmental procedure that generates a phenotype from a genotype, one or more evaluation procedures that calculate performance scores, and a feedback procedure that performs genetic reproduction based on the performance scores.

For designs with limited variability, the developmental procedure can use direct parametric modelling. However, in cases where greater variability is required, the developmental procedure may require a more complex transformation process.

These complex types of developmental procedures are commonly referred to as 'computational embryogenies' (Bentley and Kumar, 1999).

Embryogenies are a special kind of genotype to phenotype mapping process widely used in explorative evolutionary systems as they provide the mechanism for generating more complex solutions. This paper focuses on how designers explore embryogenies for specific design scenarios through an adaptive-iterative process. Previous research by Bentley and Kumar (1999) on computational embryogenies has typically focused on their behaviour and efficiency of search and their scalability for evolving different morphologies. More recently, both Dillenburger et al. (2009) and Janssen and Kaushik (2013) have proposed evolutionary design approaches for the automatic arrangement of building volumes on a given site. Although generative and evolutionary design is an on-going research topic, little attention has been paid to the process of how designers might create such embryological procedures for specific design scenarios.

As a demonstration of this process of exploring an appropriate embryogeny, this paper presents a case-study of creating an embryogeny for generating complex spatial configurations for a thesis project at the National University of Singapore.

In the case study example presented in this paper, the process of constructing an embryogeny involved four versions of adaptive-iterative exploration, each described in more detail in Section 4.

2. Design Scenario

The design scenario focuses on the need for Singapore to become more self-sufficient in terms of food production, since it imports over 90% of its food requirement (Osman, 2011). Hence, as a long term strategy to ensure food resilience for Singapore's growing population, a prototypical urban farm typology catering to a population of 10,000 people is proposed. The idea would be to have a decentralised network of such urban farms across various parts of Singapore.

State-of-the-art farming methods would allow essential food items such as vegetables and fruits, fish and chicken to be grown vertically and simultaneously within the same building. The urban farmers who grow the food were to live within the same complex as well. Also, in order to produce a part of the energy to power the building, it was decided to grow algae (bio-fuel) on photo-bio-reactor pipes to be fixed to the parts of the façade receiving the most solar radiation. The market, seed storage, waste recycling centre and many other allied spatial systems were to be located within the complex.

Each of these spatial functions has individual daylight requirements and adjacency rules that must be satisfied for its optimum functioning. For example, the

vegetable growth chamber must have adequate daylight, whereas the chicken growth chamber requires controlled daylight. The latter should preferably be far away from the farmers' housing but closer to the markets. The fish growth chambers need to be at lower floors for structural reasons but as close to the vegetable growth chambers as possible. Such complexity of the spatial and functional interrelationships and constraints means that a complex embryogenic type of developmental procedure is required.

2.1. TOOLS

The developmental and the evaluation procedures were defined using a Visual Dataflow Modelling (VDM) approach using Houdini, an advanced procedural CAD application (Janssen and Chen, 2011a). Modelling in a VDM system consists of creating dataflow networks using nodes and links. Each node can be thought of as a function performing an action and a link is used to connect the output of one function to the input of another function. VDM systems are increasingly being used as an important tool in performance-based design approaches (Shea et al., 2005; Coenders, 2007; Lagios et al., 2010; Toth et al., 2011; Janssen and Chen, 2011b; Janssen and Kaushik, 2012).

The evolutionary algorithm was executed using Dexen, a distributed execution environment. The feedback procedure, generated automatically by Dexen, will rank groups of phenotypes using a standard Pareto ranking method, and will then create new genotypes using standard crossover and mutation operators (Janssen et al., 2011).

3. Exploring Embryogenies

An embryogeny is a process of growth that defines how a phenotype is generated from a genotype. For example, in nature, embryogenies indicate how an animal should be grown. Hence the genotype may be regarded as a set of 'growing instructions', or a recipe that defines how a phenotype will be developed.

Current computational embryogenies can be classified into three different types: external, explicit and implicit (Bentley and Kumar, 1999). External embryogenies can be imagined to be a piece of computer code that performs a one to one mapping from genes to parameters and the process is not generally evolved. An explicit embryogeny is where every step of the growth process is explicitly specified as instructions in the data structure. Typically, the genotype and the embryogeny are combined and are allowed to evolve simultaneously. The third type, the implicit embryogeny, does not explicitly specify each step of the growth process, but is implicitly coded by a set of rules or instructions. By evolving a set

of simple rules which can then be iteratively applied to each element of the growing solution, it is believed that many large scale problems can be tackled.

For the purpose of this design scenario, versions of varying complexities of external embryogenies were used for evolutionary exploration. These versions became progressively more complex and less abstract. One of the reasons for using external embryogenies is that the user retains more control over the final evolved form. Moreover, one can constantly improve the quality of evolved designs by making careful modifications to the embryogeny. However, one must ensure that this complex mapping process will always produce a legal phenotype and overcome a common issue with such complex developmental procedures, referred to as the variability problem (Janssen, 2004).

3.1. VERSION 1

For the first exploration, the design problem discussed above was split into a set of cubes that were allowed to float on an abstract site of 250m by 250m. Each cube represented a fragmented part of the various functions in the urban farm and was spatially positioned within a 3d grid, as shown in Figure 1.

The embryogeny used a direct representation for defining the positions of each of the cubes within the 3d grid. The genotype consisted of a set of real-valued

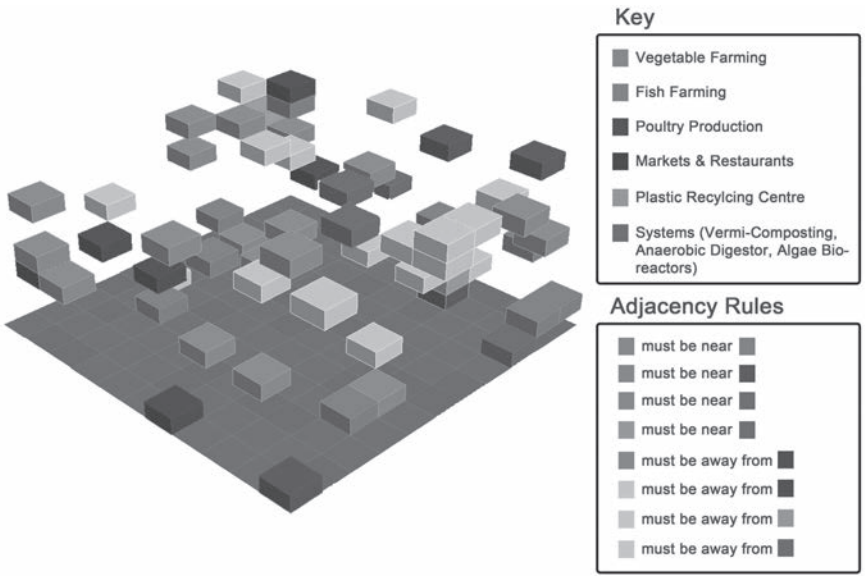

Figure 1. Floating cubes – version 1 of embryogeny exploration.

genes in the range {0,1}. For each cube, the position was defined by three genes, which were mapped to a 3d coordinate position in the grid. No constraints whatsoever were set and hence cubes were allowed to float in space and multiple cubes were allowed to occupy the same position in the grid. Each phenotype was then allocated an overall fitness score by evaluating certain simple adjacency rules for each cube. The performance criteria for the evolutionary algorithm were to maximise the number of cubes satisfying the adjacency rules. An example of one of the design variants is shown in Figure 1.

The aim of this experiment was to acquire an overall understanding of the behaviour of the cubes under the influence of the various adjacency rules. It was expected that the unconstrained freedom of position of each cube relative to all others would allow a variety of promising spatial patterns to be identified. However, although the exploration produced many phenotypes that satisfied most of the adjacency rules, it was very difficult to evaluate them visually and understand their behaviour due to their high variability. The main reason identified for the chaotic variability was the lack of constraints. Hence, in the next stage, additional constraints were introduced.

3.2. VERSION 2

In version 2, two constraints were introduced: cubes were not allowed to float, and multiple cubes were not allowed to occupy the same position in the grid. The same genotype representation was used, consisting of three real-valued genes in the range {0,1} for each cube. Two genes were mapped to a 2d coordinate position in the grid and the third gene was used to define the stacking order of the cubes. All the cubes with the same 2d coordinate were sorted according to the stacking gene, and were then stacked in that order, starting from the ground up. An example of one of the design variants is shown in Figure 2.

As expected, certain patterns and groupings emerged among the various functions. However, the variability among the solutions remained chaotic. Two key deficiencies were identified: the vertical circulation of the cubes was not clear due to the lack of cores, and the floor areas required for each function was not constrained.

3.3. VERSION 3

From the solutions generated from the previous versions, it was decided to group certain functions into a tower and podium typology. The tower consisted of four functional types; farmer's housing, vegetable farms, chicken farms and fish farms. All other allied functions were grouped together to form the podium. It was also decided to opt for a smaller site of 150m by 180m, with real surroundings that would have a bearing on the evolution of a podium and tower building. For the

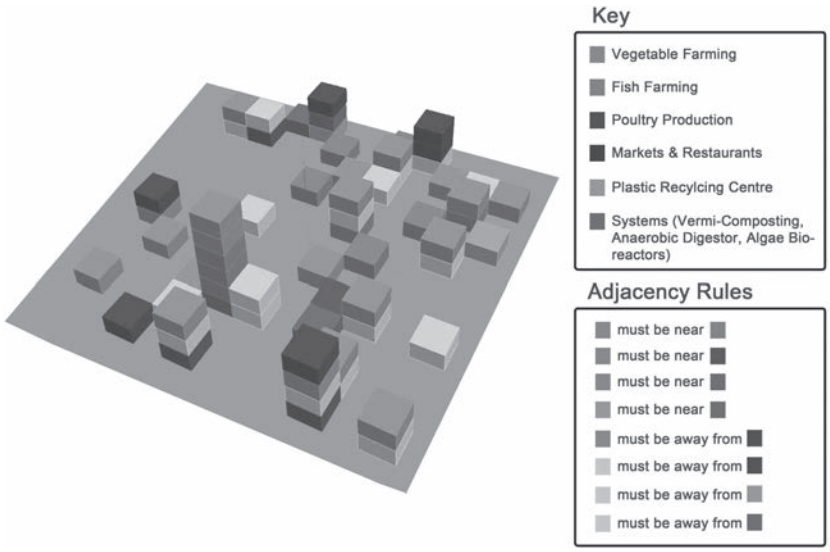

Figure 2. Stacking cubes – version 2 of embryogeny exploration.

purpose of simplifying the search space, the focus of version 3 was only to evolve the tower, assuming a fixed podium block as a base of the tower.

The tower's core consisted of four independent sub-cores (one for each function in the tower) with each catering to its respective part of the floor plan. These sub-cores were structurally integrated but functionally independent. This ensured that at any floor level, functions could be arranged in a flexible manner.

The developmental procedure used a combinatorial parametric modelling technique for generating the floor plans. Each floor consisted of four rectangles of varying sizes, with different functions assigned to each rectangle. The genotype consisted of a total of 240 genes, 12 genes per floor and three genes per rectangle. One gene was used to select the shape of the rectangle from a set of predefined possibilities; one gene was used to indicate the orientation of the chosen rectangle around its sub-core, and one gene was used to select the function of the rectangle. Three variants of the floor plan configuration are shown in Figure 3.

The fitness scores were based on a number of evaluation criteria, such as sufficient daylight for the food growing chambers and the farmer's housing, scenic views and privacy for the housing, and percentage of façade that could be utilised for growing algae with photo-bio-reactor pipes.

It was also decided to add a constraint that would limit the floor areas assigned to each of the four functions. The required floor areas are known in advance, and a technique was therefore required for defining this as a constraint within the evolutionary

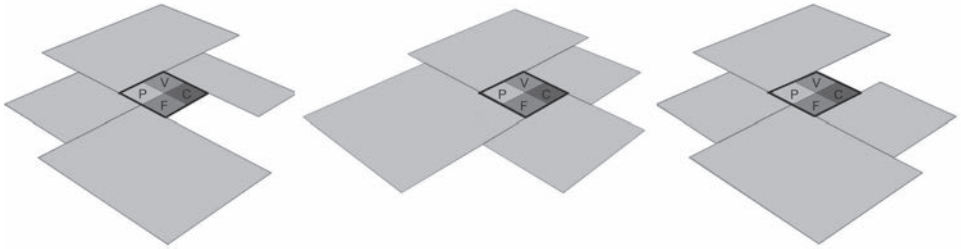

Figure 3. Variants of floor plan configuration.
P-farmer's housing, V-vegetable farm, C-chicken farm, F-fish farm

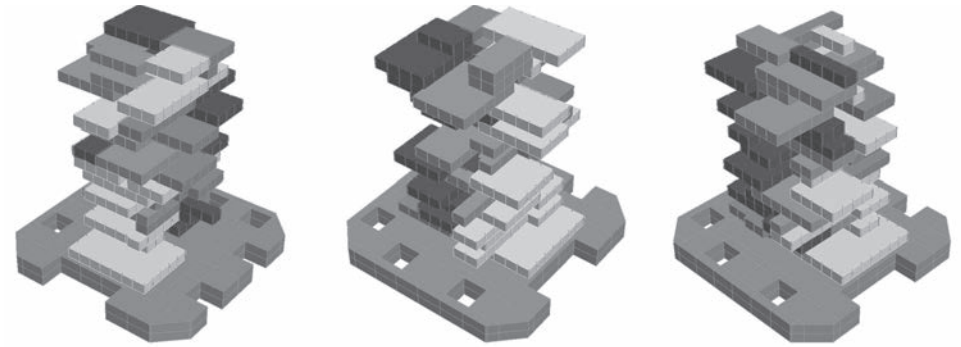

Figure 4. Phenotypes from version 3 of embryogeny exploration.

system. Researchers have identified four main approaches to handling constraints in evolutionary algorithms: 1) penalty functions 2) repair functions, 3) specialised reproduction operators, and 4) specialised genotype to phenotype decoder functions (Eiben and Smith, 2008). For this version, a penalty function was added that reduced the fitness of those solutions where the area assigned to each function was not desirable.

The solutions from the evolutionary exploration of this version indicated that certain aspects of a tower design such as the structural grid had to be refined. In addition, the penalty function resulted in many variants with very low scores, which degraded the ability of the evolutionary algorithm to evolve high performance designs. Figure 4 shows three variants from the population of evolved designs.

3.4. VERSION 4

After analysing the results from the previous version, it was decided that the size and shape of the floor plan should be defined in multiples of a specific structural

grid. After careful analysis, a structural grid of 7.2m x 7.2m was adopted as it was found to be well suited for all the four functions in the tower.

It was also noted that the use of a penalty function for constraining the floor areas of the different functions was not successful. In this version, this constraint was embedded within the developmental procedure, using a rule based decoder function that combined direct and indirect mapping of genotypes to phenotypes. This approach falls under the fourth category of constraint handling techniques as described by Eiben and Smith (2008). In this case, the genotype to phenotype mapping process was structured as a sequential chain of decisions (for more details see Janssen and Kaushik, 2013).

Each floor consisted of four rectangles of varying sizes, each overlapping with one of the sub-cores. The dimensions of each rectangle were defined as a multiple of 7.2m. As with the previous version, the rectangles were assigned different functions. The genotype consisted of a total of 180 real-valued genes in the range {0,1}, 9 genes per floor. The first 8 genes were used to specify the dimensions of the rectangles. The genes were mapped to integer values in the range {0,4} (resulting in a maximum of four grids of 7.2m each from the edge of the core). This mapping procedure is shown in Figure 5.

The ninth gene was used to select how the different functions were assigned to the four rectangles. In total, there were 21 different ways of assigning functions to the rectangles. Six of the 21 configuration are shown in Figure 6. However, in order to constrain the floor area assigned to each function, a filtering process was first performed. Those configurations that would result in excess floor area being assigned to any of the four functions were filtered out as being invalid. The ninth gene was then used to select one of the remaining valid configurations by mapping it to an integer value in the range {0,n}, where n was the total number of valid configurations. This ensured that all design variants were assigned approximately the required floor areas for the four functions.

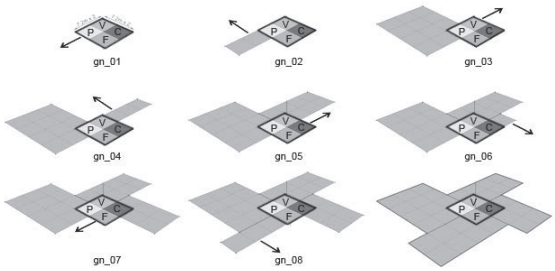

Figure 5. Developmental procedure of version 4 of embryogeny exploration. P-farmer's housing, V-vegetable farm, C-chicken farm, F-fish farm.

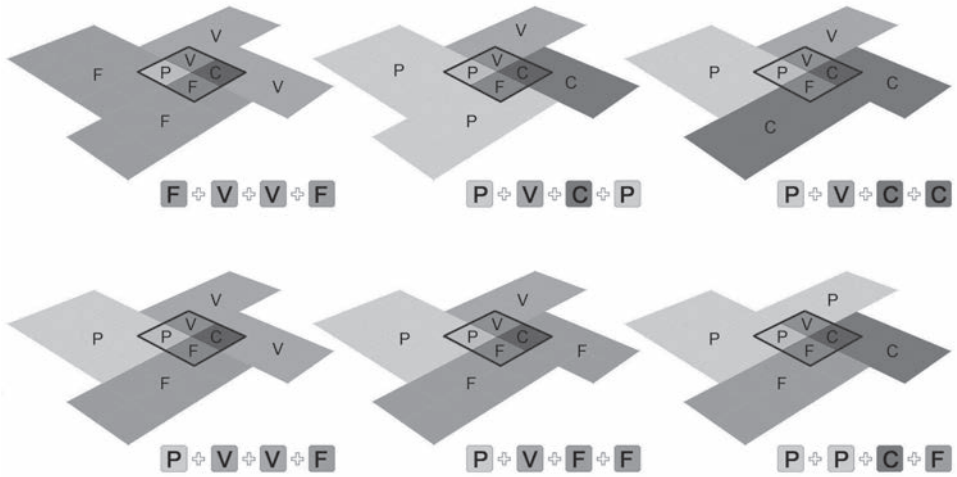

Figure 6. Few options of assigning the functional configurations. P-farmer's housing, V-vegetable farm, C-chicken farm, F-fish farm

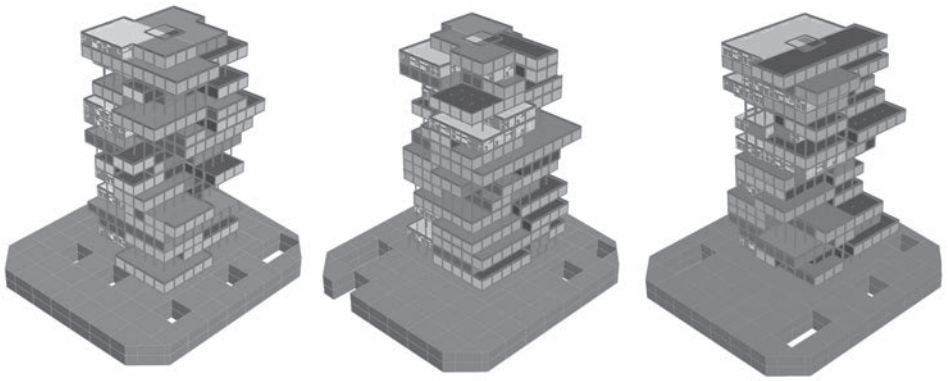

Figure 7. Phenotypes from version 4 of embryogeny exploration.

In this version, the control of variability was improved significantly and as a result the evolutionary exploration produced solutions with better performance. Figure 7 shows three examples of evolved designs.

4. Conclusion

This paper focussed on the process of creating embryogenies for a complex design problem through a sequential process of adaptive-iterative exploration. At each

version, the solutions that were evolved were not interpreted as optimal answers, but as diagnoses of potential problems and as suggestions for further architectural explorations (Caldas et al., 2001). Also as Dawkins (1988) points out, certain embryogenies are better than others at producing certain morphologies and hence it is essential for designers to explore such trade-offs through a trial and error process. By employing an adaptive-iterative process, the embryogeny can be made progressively more complex and less abstract, thereby allowing the exploration to be guided by the designer.

References

Bentley, P. and Kumar, S.: 1999, Three ways to grow designs: a comparison of evolved embryogenies for a design problem, *Proceedings of the Genetic and Evolutionary Computation Conference*, Morgan Kaufmann, 35–43.

Caldas, L. and Rocha, J.: 2001, A generative design system applied to Siza's school of architecture at Oporto, *in* J. S. Gero, S. Chase and M. Rosenman (eds.), *Sixth Conference on Computer-Aided Architectural Design Research In Asia (CAADRIA'01)*, Sydney, Australia, 253–264.

Coenders, J.: 2007, Interfacing between parametric associative and structural software, in Y. Xie and I. Patnaikuni (eds.), *Proceedings of the 4th International Conference on Structural and Construction Engineering*, Taylor & Francis, London, 63–68.

Dillenburger, B., Braach, M. and Hovestadt, L.: 2009, Building design as individual compromise between qualities and costs: a general approach for automated building generation under permanent cost and quality control, *Proceedings of the 3rd International Conference on Computer Aided Architectural Design Futures*, 458–471.

Eiben, A. E. and Smith, J. E.: 2008, *Introduction To Evolutionary Computing*, Springer.

Frazer, J.: 1995, *An Evolutionary Architecture*, AA Publications, London.

Janssen, P. H. T.: 2004, A design method and computational architecture for generating and evolving building designs, PhD Dissertation, The Hong Kong Polytechnic University.

Janssen, P. and Chen, K. W.: 2011a, Visual dataflow modelling: a comparison of three systems, *Proceedings of the 4th International Conference on Computer Aided Architectural Design Futures*, Liege, Belgium, 801–816.

Janssen, P. H. T. and Chen, K. W.: 2011b, Iterative virtual prototyping: performance based design exploration, *Proceedings of the 29th eCAADe Conference*, Ljubljana, Slovenia, 253–260.

Janssen, P., Chen, K. W. and Basol, C.: 2011, Evolutionary developmental design for non-programmers, *Proceedings of the 29th eCAADe Conference*, Ljubljana, Slovenia, 245–252.

Janssen, P. H. T. and Kaushik, V.: 2013, Decision chain encoding: evolutionary design optimization with complex constraints, *Proceedings of the 2nd EvoMUSART Conference*, Vienna, Austria, 157–167.

Lagios, K., Niemasz, J. and Reinhart, C. F.: 2010, Animated building performance simulation (ABPS) – Linking rhinoceros/grasshopper with radiance/daysim, *Proceedings of SimBuild '10*, New York.

Osman, M. M. B.: 2011, "Speech by Dr Mohamad Maliki bin Osman, Senior Parliamentary Secretary for National Development and Defence at the opening ceremony of the International Conference on Asian Food Security". Available from: Ministry of National Development <http://app.mnd.gov.sg/Newsroom/Speeches.aspx/> (accessed 15 February 2011).

Shea, K., Aish, R. and Gourtovaia, M.: 2005, Towards integrated performance-driven generative design tools, *Automation in Construction*, **14**(2), 253–264.

Toth, B., Salim, F., Burry, J., Frazer, J., Drogemuller, R. and Burry, M.: 2011, Energy-oriented design tools for collaboration in the cloud, *International Journal of Architectural Computing*, **9**(4), 339–359.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 147–156. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

A MINIMAL TENSION CANOPY

Through investigations of self-organised systems

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Abstract. The dynamics of a physics-based algorithm which acquires its complex organization through a number of localised interactions applied over a prescribed network can be described as a self-organised system. This in turn has the capacity to define explicit form and space based upon behavioural computational processes with an embedded structural logic. This paper discusses the way in which physics based algorithms can be used to inform the organisation of a compressional structure in a case study. Its structure is based on Hooke's law of elasticity; which establishes a three dimensional catenary logic through a number of localised interactions applied over an entire network. This is applied to a project with specific constraints to site, boundary conditions and maximising solar gain whilst maintaining structural rigidity. The methodological approach describes the design to assembly process in which the project has been developed. This includes the applied generative design tools in order to establish the self-organised logic, the form finding process, the techniques of design documentation, the fabrication process and the logistics of construction and assembly.

Keywords. Digital fabrication and construction; generative; parametric; simulation.

1. Introduction

Self-organised systems can be described as a dynamic and adaptive process through which systems achieve and maintain structure without external control (Hensel et al., 2006). These systems allow for a computational exploration of a high level of structural performance, and can then be intrinsically linked to the material system of which it will ultimately be fabricated. Albeit analogue, Frei Otto's pioneering work within the field of minimal surfaces and lightweight high tensile membranes went far beyond traditional methods of calculating structural stresses. His work includes clear examples of self-regulating building elements developed through the specific material organization of their interrelated parts. This technical approach to understanding natural systems makes use of the physical laws which were discovered in order to develop new strategies for design (Gruber, 2008).

A process of form finding is established through computational methods which are not bound by the composition of subjective criteria, but instead a product of qualified feedback through parametric and multi criteria controls. These investigations lead to new and unbiased understandings of architectural space and geometry which permit a dynamic and adaptive interchange between concept, organization, structure, materiality and its resulting space.

Algorithmic design through the use of software environments such as McNeel's algorithmic editor Grasshopper and its custom Visual Basic scripting component enables the development of rule sets. Different criteria can be played out using timers that simulate the generative process of self-organisation. Thus, a logical framework emerges during the schematic stage of design, which may be adjusted and repositioned as the intrinsic part of a generative design process. Focus on such an analytical methodology seeks not only to document pre-existing design nodal types or ancestral trees, but also provides an opportunity to investigate diffuse typologies of hybrid process & multi-material performance through a recombination of scripts and algorithms.

Exploration of design via scripting and making techniques seeks to identify a universal language of code assembly and accessing digital technology as part of everyday practice (Burry, 2011). Rather than the serial progression of macro code which executes one line after another, scripting language introduces loops, conditional statements and other forms of checking to control the flow of construction in the development process.

Within the framework of the case study presented here the scripted environment allows for a number of factors to be considered which have explicit relationships between each other. The project has been developed using a particle system which sets out the criteria for form finding, the programmatic influences

of the proposal, the constraints of the site and the restrictions of the material applied. The optimization between each of these elements results in an explicit outcome derived from a logical framework of inputs.

2. Case Study Minimal Tension Canopy

The use of a physics based algorithm for developing a self-organised structural roof canopy is discussed in the following via a design proposal for a 3rd floor constrained apartment terrace located in Sydney's CBD. The site is defined by a number of constraints: it is approximately 10m x 5m and is located to the rear of the building. The building has a total of 34 storeys and the terrace receives the brunt of debris which the neighbours above throw from their balconies. The terrace contains two large skylights which filter light to the communal gym area below which cannot be obstructed. Limited penetrations can be made on site particularly to the tiled flooring in order to maintain a waterproof seal to the levels below. In addition site access is limited to a 2.1m x 2.1m lift restricting the size of structural elements that can be delivered to site. Overall the terrace was seen as unsafe for the client and his family to use and therefore the brief called for a lightweight canopy that would filter debris into safe collectable containers, maintain solar amenity for the level below and create a safe outdoor space for entertainment (Figure 1).

The design challenge was to build a structure using a number of serialised components which could be assembled easily and efficiently on site. The structure needed to be self-supporting and allow for breaks or holes within the network in order to maintain the solar amenity to the level below. The design intent was to develop a canopy which was an informed relaxation membrane and one which did not exert any lateral loadings to the building. Precedents for this system came in the form of Otto's Mannheim grid shell structure and in particular the British Museum Great Court developed by Chris Williams (2004).

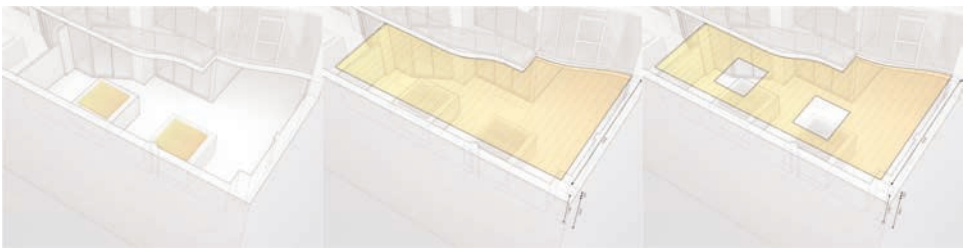

Figure 1. Diagram describing the constraints of the site.

3. Catenary Logic

The logic of a catenary curve suited the design intent in which a self-regulated arch could be produced supporting its own weight at its ends. Hooke's law of elasticity provides an approximation stating that the extension of the spring is directly proportional with the load applied to it. This could be applied to the catenary curve allowing varying degrees of elasticity to be exerted depending on its positioning and forces applied.

The catenary curve is a one dimensional cable network whereby a line or curve is split into a series of straight segments, with each segment acting as a spring member. In this case a number of parameters can be controlled which includes spring, damping and gravity effect on each node within the network. This exact organisation forms the building block for a two dimensional structure in which each node in the structure has effect on neighbouring nodes with respect to its topological order. In addition, further relationships between nodes such as diagonal referencing can be introduced to attend shear force moments. With the introduction of gravitational force applied to each node, a catenary surface may be developed. Creating a customised surface with breaks and edge boundaries additional characteristics need to be added. Within the sheet typology loops are created and the diagonal shear springs pull to specific nodes on each loop according to their proximity. In addition, the perimeter of the loops and overall surface are constrained in order for the surface to begin organizing itself around the given constraints (Figure 2).

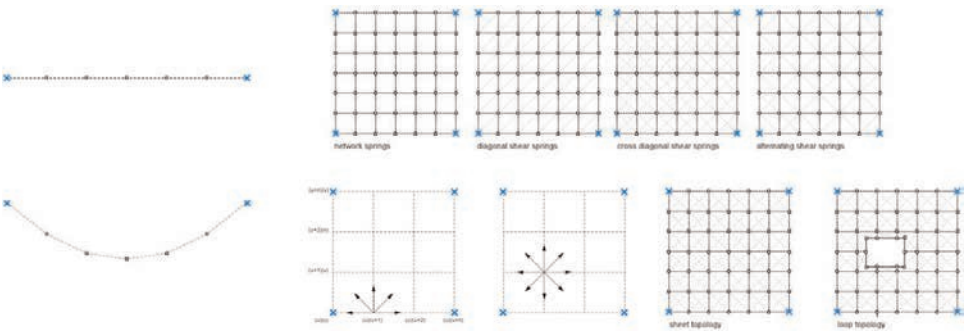

Figure 2. Catenary chain and resulting diagrams describing the catenary network logic.

4. Structure

This technique provided a clear framework in which a generic canopy structure could be organised around a number of varying constraints. The application of the

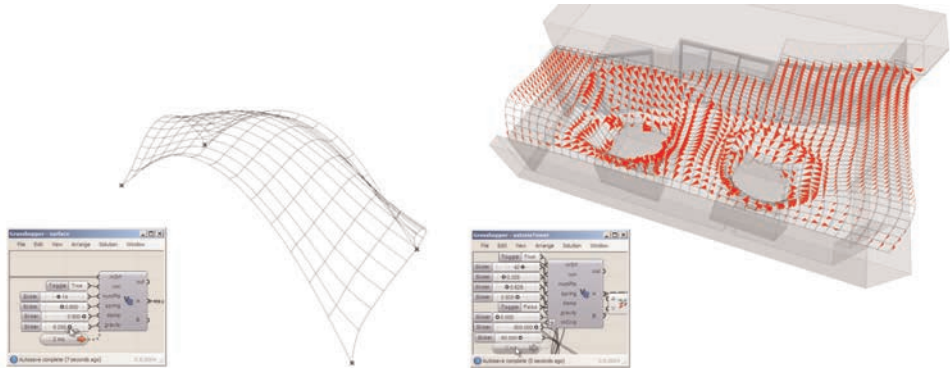

Figure 3. Simulation of catenary surface and catenary surface with loops and site restrictions.

algorithm to the specifics of this particular site could then be mapped which included the non-orthogonal site boundary, the two skylights situated in the middle of the space and a low height plane dictated by the strata lot. Once the Grasshopper definition was executed, the catenary network organized itself around its parameter constraints and settled into a self-organised and self-supporting structure (Figure 3).

Once the overall formal arrangement of the network found it's equilibrium a number of modifications were applied in order to verify the fall and angle of the surface always directed towards the skylights so to prevent debris and water collecting on flat planes. The next step was the application of a material logic that could be fabricated in an efficient manner and at a reasonable cost. The panelisation of the surface could be achieve in a number of ways but due to the restrictions of using a 3 axis CNC router and laser cutter the final components needed to be fabricated from a flat sheet.

Dividing a surface in its U and V directions so square panels are generated works for a single directional curvature. As soon as this is curved in a secondary direction the result is a splitting or fracturing of the edges. This is still achievable if the resulting structure can adopt the overlaps in its design but in this particular case a sealed and water proofed contact edge was necessary. By dividing the panels into triangles allowed for multi directional curvature of the surfaces without the splitting of the edges (Figure 4). The resulting structure was a triangular panelised surface which radiates in a polar array from each skylight.

The triangular component arrangement solves panelling a doubly curved surface, but does not resolve the structural integrity of the canopy which requires thickness for rigidity. A minimal depth of 50mm along the structural radial lines and a 50mm width to each panel was required by the engineer. The approach,

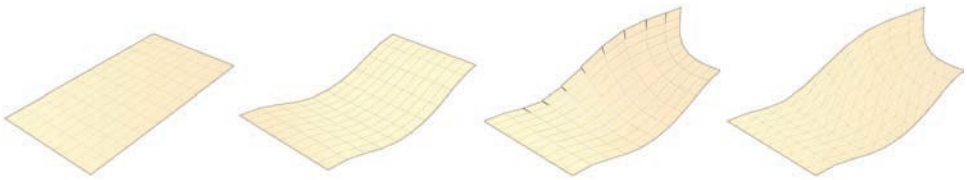

Figure 4. Diagram of panelization.

Figure 5. Completed structure.

within the constraints of the fabrication tools, led to cutting the triangular panels with a 50mm tab on each side which are folded to the correct angle using a brake press thus producing an L section profile. When connected, the triangular elements form a series of radial beams maintaining structural efficiency throughout the canopy. Earlier models allowed for a variable internal cut out for the triangular components which then control the amount of solar gain throughout the structure. This would work for a larger scaled structure which was orientated differently, however the project site is constantly overshadowed so the resulting apertures for each component had to be maximised throughout the canopy (Figure 5).

5. Documentation for Fabrication

A stick model structure was tested in the finite element analysis program Strand 7 which highlighted a number of weak points and bending moments (Figure 6). The model was optimised so that no length of any triangular component was greater than 1.5m. Each component was fabricated using 6mm aluminium sheet. Due to the constraints of the brake press each component had to be cut back 50mm from its corner point in order for the folded tabs to fit into the break press and not affect each other. The result of this was a series of gaps at each nodal point of the structure which left the radial structural paths weak. Additional stiffener plates were sandwiched between these gaps to maintain the structural rigidity of the canopy.

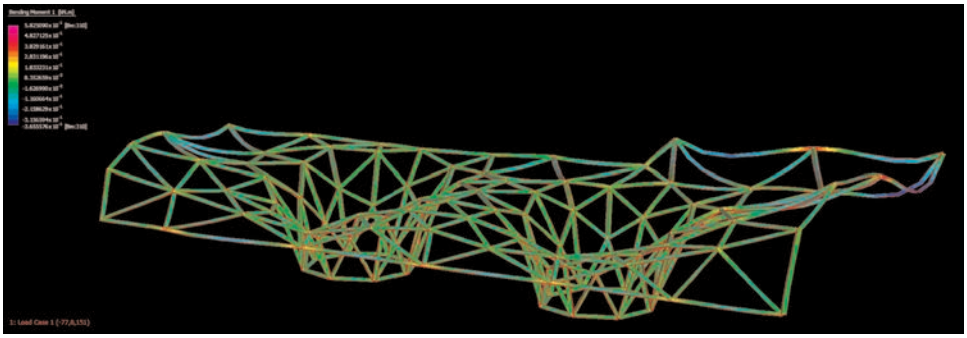

Figure 6. Visualization of finite element analysis testing.

Mapping all of this information as a parametric construct was essential in maintaining precision throughout the design and documentation phase. A three dimensional scan was taken of the site so millimetre tolerances could be maintained.

As the design developed information from the fabricator on the radial bending of the aluminium panels changed. An internal radius of 12mm was required for bending the tabs in the break press. Additionally these tabs needed to maintain their 50mm depth so that the depth settings on the break press did not have to be adjusted for each panel. This needs to be described mathematically in the parametric model which can then be updated on the fly if any of these parameters change at a later stage.

The Grasshopper definition was divided into a series of VB scripted components in order to work on the front end of the definition once key elements had been resolved. This reduced refresh time of the script allowing for parts to update quickly. Information within the model could then be broken down into segments and manipulated dynamically. This would be assemblies of part, layers, groups and geometry.

These adjustable parameters were applied to the depth of the tabs, size of bolt and rivet holes between components and connections to the perimeters walls. The number of connection holes between elements was controlled via the length of each part. If a length was less than 300mm it was allocated 2 holes. If it was more than 300mm it was allocated pairs of holes which would match its neighbours.

The three dimensional geometry was then unfolded in order to produce flat nested templates for fabrication. Each edge of each component was mapped according to its position in the model and single line fonts were applied to each edge with a bend angle (Figure 7). These were mapped as two halves, the left and the right and then sequentially from the centre of the skylights outward. This topological mapping of each components position equated to a hierarchy of parts which when assembled on site were easily read, organised and assembled.

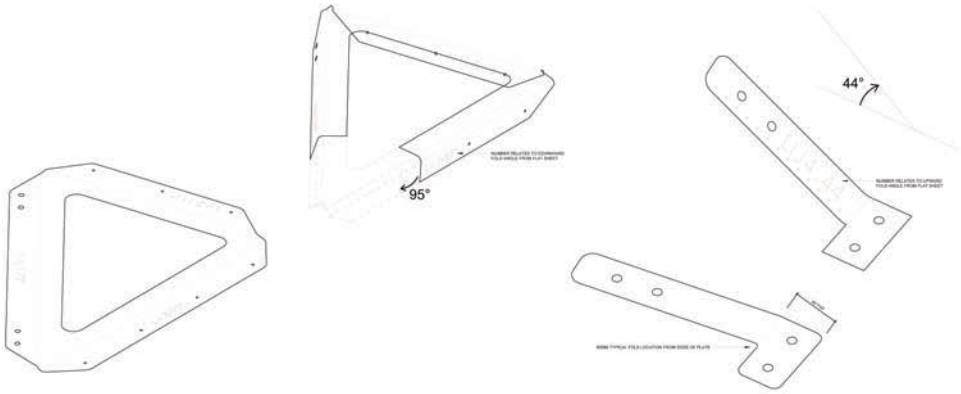

Figure 7. Diagrams for folding of parts on the brake press.

Figure 8. Diagrams for folding of parts on the brake press.

The fabrication of this project is relatively straight forward. Cutting files were supplied for both the aluminium and steel components with all parts nested with layers with lines for cutting, scoring and bending. All the aluminium components were laser cut and the steel CNC routered. The aluminium components tabs were then folded on the brake press at the correct angle for each tab (Figure 8). Steel parts were then galvanised and then all components powder coated white.

6. Assembly Logistics

Once delivered to site all of the components were organised according to their numbers and radial neighbours. A drawing indicated the order of the assembly

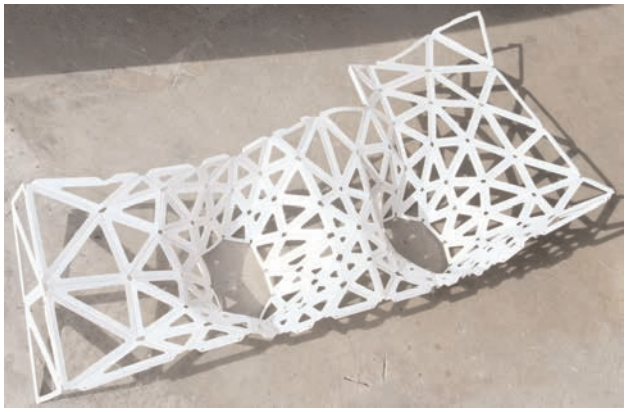

Figure 9. Physical model for assembly sequence.

sequence and a 1:10 physical model described each labelled component with the order of radial families of parts (Figure 9).

Firstly in the assembly sequence the gutter collars were positioned around the skylights. From there the central components which affixed to the gutters were positioned, bolted and pop riveted. From here these two sections were joined or bridged and once in position strips of elements were built in a radial sequence in an order which maintained structural stability. All of the components where finally tightened forming the final fitting of the structure (Figure 10).

Figure 10. Final Construction Process.

There were a number of issues that came to light during the construction process. The appointed engineer allowed for a 1mm tolerance around each pop rivet and bolt hole. This was the only tolerance within the entire structure. The result of this was as the structure grew in the number of parts connected we would have to loosen and leaver components together which was often tough work and quite time consuming. However the result of this was an extremely ridged structure. The second issue was sealing of the polycarbonate panels. Attaching each panel was extremely quick using double sided glazing tape but the application of silicon between each panel is a job and cost which we did not anticipate taking so long. This is a result of the distance between each panel varying greatly. Certain panels are up to 20mm apart which means that applying the silicon needs a lubricated backing strip which can be removed once the silicon is dry. Often the silicon will sag as it dries and creates perforations which then need a reapplication of silicon.

7. Conclusion

The work explores the potential of using physics based algorithms to describe and produce structural solutions for a constrained site which is specific to its conditions and characteristics. Although this paper describes a particular project, the framework of the system that has been scripted and the process of documentation and fabrication enable this project to become an adaptive typology, which can be developed for another program and location. The powerful nature of the parametric tools implemented throughout the project has allowed for live manipulation and adaption from design phase to documentation without loss of information or the need to laboriously redraw and reorganise information. This parametric process has resulted in a smooth sequence from design to construction through the use of customizable tools and standard fabrication processes. The case study finds a medium whereby these tools are used in a pragmatic manner to not only understand a form driven by its site constraints but though integrating constraints of structure and material logic.

References

Burry, M.: 2011, *Scripting cultures: Architectural design and programming*, John Wiley, Chichester, UK.

Gruber, P.: 2008, The signs of life in architecture, *Bioinspiration & Biomimetics*, **3**(2), 023001 (9 pp.).

Hensel, M., Menges, A. and Weinstock, M.: 2006, Towards self-organisational and multiple-performance capacity in architecture, *Architectural Design* **76**(2): 5–11.

Williams, C.: 2004, Design by algorithm, *in* N. Leach, D Turnbull and C. Williams (eds.), *Digital Tectonics*, Wiley-*Academy*, 78–85.

SIMULATION, PREDICTION AND EVALUATION

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DAYLIGHT PROTOTYPES: FROM SIMULATION DATA TO FOUR-DIMENSIONAL ARTEFACT

Physical metrics models in sustainable design education

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Abstract. The increasing use of building performance simulation in architectural design enriches digital models and derived prototyping geometries with performance data that makes them analytically powerful artefacts serving sustainable design. In our class "Parametric Design", students perform concurrent thermal and daylight optimization during the architectural ideation process, employing digital simulation tools, and also utilize rapid prototyping techniques to produce process artefacts and whole-building analysis models with climate-based daylight metrics physically embedded. Simulation metrics are merged with prototyping geometries to be output on a colour-capable Zprinter; the resultant hybrid artefacts simultaneously allow three-dimensional formal as well as whole-year daylight performance evaluation, rendering analysis scope four-dimensional. They embody a specific epistemological type that we compare to other model instances and posit to be an example of multivalent representation, a formal class that aids knowledge accretion in performance-based design workflows and allows designers to gain a physically reframed understanding of geometry-performance relationships.

Keywords. Rapid prototyping; building performance modelling; daylight simulation; physical data models; design representation.

1. Introduction: Rapid Prototyping and Performance Simulation

Digital design media has undergone several decisive paradigm changes throughout the last decades. The shift from two-dimensional CAD to parametrically responsive, data-enriched digital models has evolved the perception of architecture-in-progress from a play of static representations towards the interaction with dynamic codifications of constraints and form. In parallel, rapid prototyping (RP) techniques have established a direct link with subsets of the material realm. These developments

have fundamentally influenced the way architectural design is practiced, taught and researched, both on the level of design epistemology and in the way representative process artefacts are understood (Sass and Oxman, 2006). With the formal and functional possibilities of the dynamic ideation-production complex tentatively established, attempts are currently being made under the auspices of sustainable architecture to integrate simulation-based performance prediction into the mainstream of environmental design activities (Venancio et al., 2011; Hetherington et al., 2011). Consequently, RP models become linked to simulation data sources, yet still exist as their own epistemological category. How data-rich design environments can imbue them with additional representational and analytical properties is explored in this paper; previous work on data-embedded prototypes performed at the Milwaukee School of Engineering acts as proof-of-concept precedent (Bolda, 2008).

1.1. CLASS BACKGROUND AND PAPER STRUCTURE

The class "Parametric Design", during which the 1:250 scale daylight models presented in this paper were generated, teaches energy and daylight simulation in a design context. Students create their own building layouts, in the discussed semester based on the brief of an office building. They improve energy efficiency and daylight utilization by means of adapting architectural form using DesignBuilder, an interface to the simulation engine EnergyPlus (Crawley et al., 2000), and DIVA (Jakubiec and Reinhart, 2011), a daylight simulation plugin for the modeller Rhinoceros3d.

One of three sites in different climate zones (Östersund, Sweden; Hashtgerd, Iran; Ft. Lauderdale, Florida, USA) is to be individually chosen by students, resulting in designs that are in massing and envelope visibly attuned to the respective environmental conditions. Studies of alternative construction materials and passive conditioning are not part of the class, since it is primarily concerned with the comparative effects of building geometry. As such, the final artefacts built by students would in reality likely not reflect the last iteration but instead serve as an evaluation milestone; the models are thus regarded as in-process representations outlining intended form.

Three main assignments take students through the design-optimization process, beginning with heuristic design seed generation, continuing with partial simulations and finally encompassing whole-building calculations. Optimization is achieved by investigating geometric properties like orientation, window-to-wall ratio changes and fixed shading devices. Despite featuring iterative evaluations, integrated design is usually not a linear or rational activity, as previously reported by the authors. Instead, cross-domain representations serve to continuously enrich form-performance knowledge, which in return improves heuristic decision-making (Doelling and Nasrollahi, 2012). The artefacts discussed

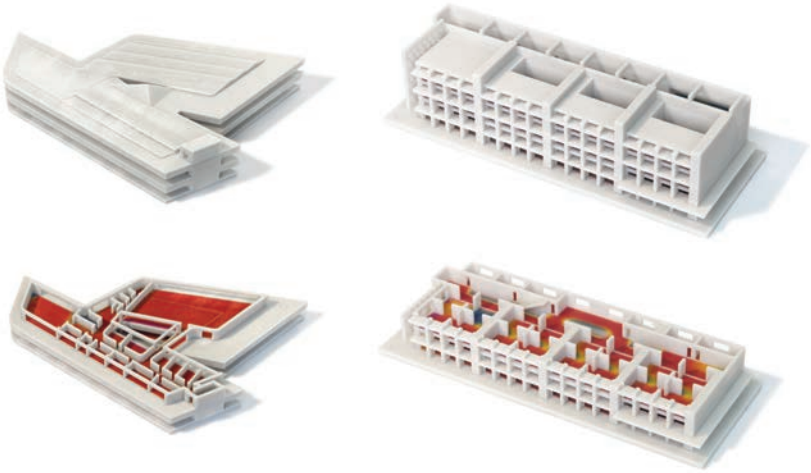

Figure 1. Rapid-prototyped daylight models, Florida (left) and Iran (right), with DA 300 and UDI 100–2000 lux metrics embedded.

herein accompany this process; whole-building metrics models are preceded by test geometries to gradually approach a holistic design state. This paper presents two physical daylight models (Figure 1), their prior test artefacts and positions them in the overall workflow. It provides the theoretical background of daylight simulation and explains model production. Finally, we derive the models' representational and processual properties and discuss their usefulness for sustainable design.

2. Daylight Prototypes: General Properties

Since light behaves identically at life-size and model dimensions when surface properties are analogous, simulation scale models have been used extensively in architectural design. Digital daylight evaluation has now surpassed previous methods in analytical scope, hence main simulation work in our class is performed by computing climate-based daylight metrics that display the percentage of inhabitant-occupied hours of a whole year when illuminance meets a set target (Reinhart and Wienold, 2010). The prototypes show the metrics "Daylight Availability" (DA) in office spaces, tuned to 300 lux as per IESNA recommendation (Rae, 2000) and "Useful Daylight Illuminance" (UDI) 100–2000 lux embedded in non-office spaces with varying daylight requirements. UDI values of 100 to 2000 lux, which are generally useful (Nabil and Mardaljevic, 2006), describe an illuminance range that indicates the remaining zones' overall daylight potential.

In the model-embedded metrics, orange to red colours denote good performance (ca. 70 to 100% of occupied time target illuminance reached), while yellow to blue for UDI spaces indicates either partially overlit or underlit conditions. Pink colours in the DA metrics show areas that exceed 300 lux at least 5% of yearly occupied hours, with underlit areas indicated as in the UDI scheme. Results are shown with no additional dynamic shading devices used, which stays in tune with class intent: a building that by its geometric nature reduces the overall occurrence of overlit areas offers a better starting seed for further optimization work. Surface reflectances and visual transmittance values, however, are fully accounted for.

To facilitate viewing of all spaces, models can be disassembled, inviting them to be handled; a north arrow is included in each base, since knowledge of a building's orientation is essential to understand performance.

2.1. INDIVIDUAL DAYLIGHT PROTOTYPES

Out of the many models produced, we discuss designs situated in Iran and Florida. The annual average dry bulb temperature in Ft. Lauderdale is 25° C; intense insolation occurs the entire year (1792 kWh/m^2 cumulative horizontal irradiation), with summer tendentially overcast; in winter, direct sunshine prevails. Providing continuous shade and attenuating sunlight is important for daylighting purposes and to reduce cooling energy consumption.

The design (Figure 2) features large overhangs that shade all façade orientations and double as a continuous balcony; light is scattered by additional horizontal louvers into a diffuse field that still allows for comparatively large window openings usable to achieve cross-ventilation.

In initial versions, vertical louvers were proposed and physically tested with a selectively laser-sintered model. Successive digital simulations further investigated their performance and the effect of varying overhang widths, revealing that using horizontal louvers only yields best results. Additional North-facing skylights allow for deep daylight penetration with low thermal trade-offs, further aided by a shielded courtyard acting as a light-well. Total projected energy demand for heating, cooling and lighting was reduced throughout the design process from 111 kWh/m^2 to 68 kWh/m^2; final DA 300 lux utilization is 84% of occupied hours, UDI 100–2000 90%.

The second design is situated in Hashtgerd, Iran. Clear skies predominate (1951 kWh/m^2 cumulative horizontal irradiation) and strong seasonal temperature variations exist, giving an average annual dry bulb temperature of 15°C. Thermal solar gains are welcome in winter and to be prevented in summer. Thus, the envelope looks entirely different (Figure 3), also a result of the solar geometry at Hashtgerd's more northern latitude.

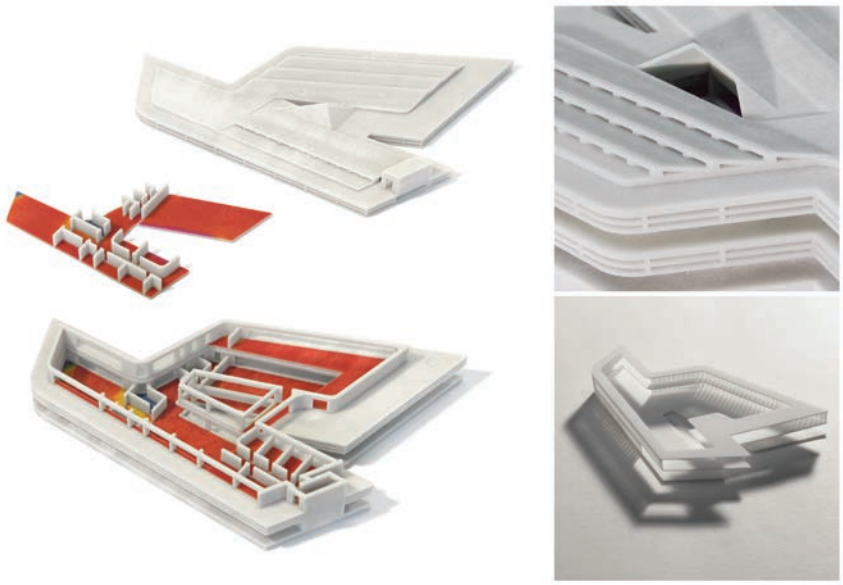

Figure 2. Florida sintered test model, skylight/louver detail and final RP model shown disassembled with DA 300 and UDI 100–2000 lux metrics visible.

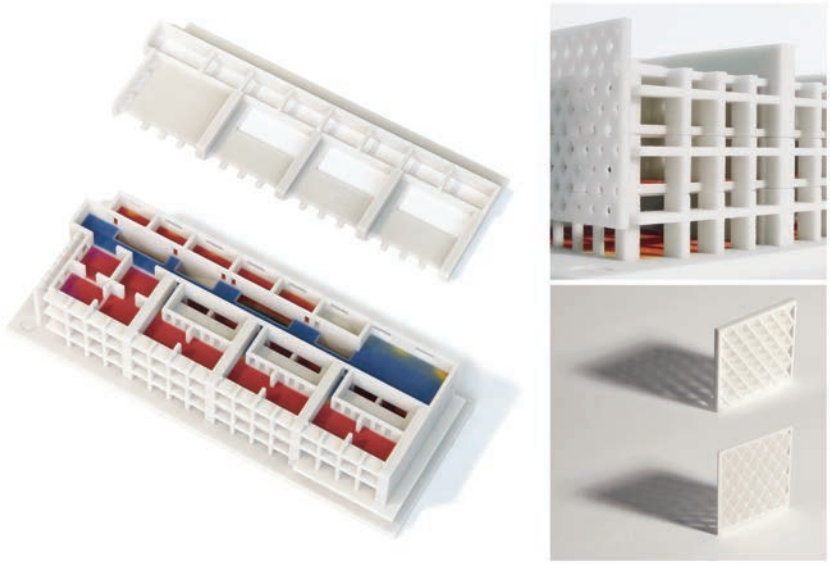

Figure 3. Iran sintered shading geometries, facade detail and final RP model shown disassembled with DA 300 and UDI 100–2000 lux metrics visible.

A key design strategy is the use of a south facade that is deep in section. Fixed overhangs and fins shield from high altitude, glancing angle summer sunshine, and overhangs additionally act as light shelves to increase daylight depth. In effect, the average yearly daylight distribution is excellent, however seasonally more varied than in the Florida design and exhibiting some overlit areas due to low winter sun angles.

A large atrium along the building's spine allows light to reach the second-storey back offices, which also receive illumination from skylights. Prototyping tests additionally focused on a diamond-grid shading structure on the West façade, intended to allow views and limit summer gains, which was iteratively laser sintered and tested in several independent variations, ultimately influencing the façade layout. Total heating, cooling and lighting energy demand was reduced from 54 kWh/m^2 to 46 kWh/m^2; daylight utilization is 70% for DA 300 lux and 78% in the UDI 100–2000 range.

3. Process: Data Preparation and Model Production

The class workflow relies on the parallel use of thermal, daylight simulation and conceptual design models. It constitutes a heterotopia of tools and representations specific to the epistemological interest at hand; how their domain of permutations is navigated has decisive influence on the simultaneous discovery and actualization of design intent. In general, students attempt to align spatial parameters with specific simulation investigations by means of synthetic representations; performance and form are judged in unison, mediated by simulation data embedded in digital and RP models.

The plugin DIVA links the dynamic daylight simulation tool Daysim (Reinhart, 2006) to Rhinoceros3d. It employs a daylight coefficients approach (Bourgeois et al., 2008) to numerically encode the mediating effect building geometry has on the ability of virtual sensors to receive specific fractions of sky luminance during each hour of the year. This allows sets of new metrics to be generated quickly if occupancies and illuminance targets shift. EnergyPlus weather files comprised of real-world measurements are used, identical to the ones employed for the thermal simulations. These files describe typical site conditions taken from multi-year data (Wilcox and Marion, 2008).

Simulation models are built as 1:1 scale NURBS geometries in Rhino and usually also serve as conceptual design models; they share analogous quality requirements with derived RP models, most importantly topological mesh validity and avoidance of coplanar surfaces. Daysim requires polygon mesh input, therefore complicated geometries were often pre-meshed for precise export, a step that must also be performed with RP geometries. These similarities establish a layer of

logical workflow connections that semantically unify the production process. Before prototyping, students commonly rebuild geometries at model scale to maintain a balance in proportions, in itself an aesthetic decision, and as prefiguration of desired tactility chose which parts of the model are to be made detachable. Daylight metrics textures are derived from DIVA results grids, in Rhino 5 assigned to densely triangulated floor planes and baked into the vertices to remain fixedly embedded.

Gypsum-based RP models are printed layer by vertical layer; clear and coloured binder is sequentially deposited on a proprietary substrate that is spread over the build area to materialize each model slice. Special consideration is given to the used ZPrinter's specifications, e.g., avoidance of features less than approximately 1.5mm in thickness, as they are too sensitive to handle in post-processing. The physical artefact is fragile upon removal from the machine and needs to be sealed with clear, low viscosity epoxy; this procedure gives models the desired robustness to withstand continuous handling, one of their important properties.

4. Conclusion: Model Epistemology and Design Education

Having described the class background, select prototypes and production procedures, we now need to synthesize the models' properties and elucidate their applicability in the practice of sustainable design education.

Simultaneously negotiating a multitude of epistemes to achieve design performance actualization poses the challenge of managing the interplay of various evaluative representations. In order to achieve a semantic transfer of cross-domain information, the expressions of tools, workflows, metrics and their intended impact on design decisions need to be seen in unison, as posited in integration research (Mahdavi, 2011). In our case, the involved domains are design and daylight/thermal optimization, both enmeshed as a work-in-progress. The multi-tier strategy of articulating several assembly prototypes first, before producing the complete final models, is closely related to a workflow that relies on the steady accretion of form-performance knowledge and cannot be described in linear terms; as such, the RP models are snapshots of design intent at different advancing stages and aid the ideation process by combining spatial expressions with performance indicators.

The similarities of simulation and prototype geometry preparation bind both activities into a single, comparatively seamless space, however it is primarily the final models' properties and contained information that gives them their descriptive acuity. Traditional physical models can serve to elucidate a finished design or be used as process tools (Moon, 2005), however usually do not contain

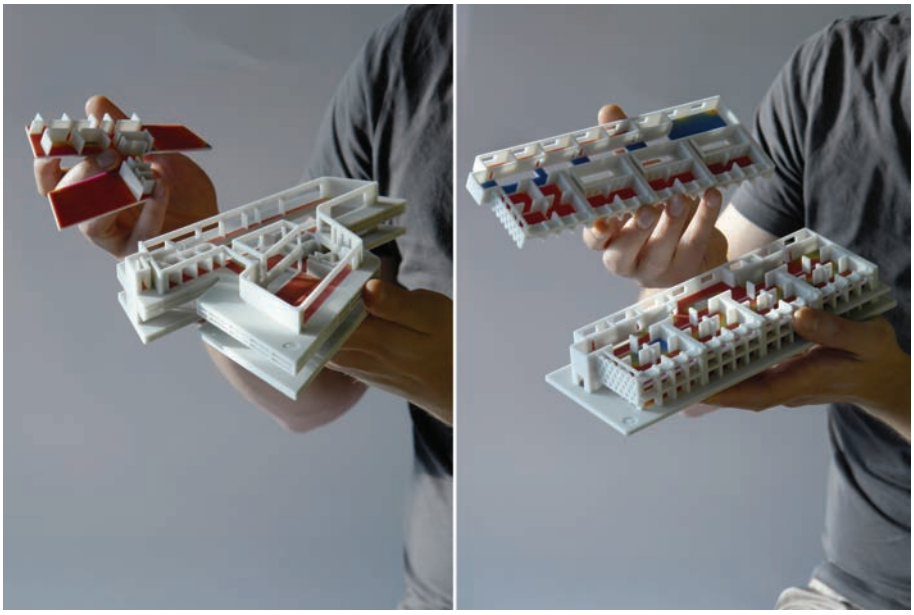

Figure 4. Florida, Iran daylight models handled and disassembled, daylight metrics visible.

performance projections. Since no advanced daylighting implements such as light-redirecting glazing or dynamic shades are used in the prototypes, their physical expression directly references the main geometric features responsible for performance. This absence of invisible modifiers lends them strong immediacy and analytical presence; only glazing transmittances and surface reflectances are not materially reproduced, yet in the discussed models have a much reduced impact on performance compared to their overall geometric properties. In-process simulation data is commonly displayed through the filtering effects of digital, projective design media; the prototypes instead allow non-projective, three-dimensional and factually invariant perception while retaining dynamic engagement, since their separation into parts and physical stability invite interaction (Figure 4).

Additionally, the climatic information used to generate the included daylight metrics contains the typical conditions at a site, not only those for one year. Hence, the prototypes become four-dimensional, since they refer to location-specific performance over time, which cannot be physically shown by artefacts not enriched with simulation data. The illuminance target specificity of the used DA and UDI metrics can also not easily be represented in traditional physical models and is unique to the RP geometries.

In summary, the metrics models enable management of multi-domain data from design and engineering epistemes by splicing together features of the architectural model, a classic representative category that principally investigates form, with data from the engineering domain of energy performance optimization; as descriptors, the models are thus truly multivalent and reflect a field state of design thinking at the end of the schematic design phase, for they allow a simultaneous, three-dimensionally mediated observation of performance and the geometrically encoded design decisions that are its cause.

4.1. MODEL APPLICABILITY IN DESIGN EDUCATION

We intensively use previous models in following classes as they make the interplay of performance and geometry literally graspable for students, summarize optimization results in a physically reframed shape and serve as a typological library. The handwriting of manual model-building is partially erased by the modes of digital fabrication that reduce designs to geometric purity, yielding precise yet abstract expressions on which new ideas can be projected. This also simplifies morphological comparisons between multiple printed prototypes across several climate zones, which is the explicit goal of our class; thermal design considerations are geometrically implied and become most apparent when directly comparing several artefacts. Also, overlit areas are often correlated with unwanted solar gains, which become visibly pin-pointed in the models. New students are thus exposed to an intuitive demonstration of geometry-performance interplay; despite no legend being included on the artefacts, when presenting them with a quick remark that “red means good performance”, observers usually quickly grasp the way a given design controls solar gains and achieves good daylight performance.

In essence, the models aim to educate upcoming class participants as much as they do the original creators, who additionally deepen their knowledge by prototyping selective performance artefacts such as the sintered façade studies also shown in this paper. These offer an experience of point-in-time shading behaviour and are then, in modified fashion, implemented in the whole-building designs, their annual performance to be finally encoded in the whole-building prototypes. As we commonly experience in teaching, projective graphical metrics display on screen or as numerical data requires much greater explanatory effort than demonstrations based on physical artefacts. The models’ ultimate power therefore lies in enhancing the understanding and communication of a specific design state as well as improving the way further adaptations are envisioned. Their meaning is readable on several epistemological levels at once, expressing more than the sum of individual parts: design synthesis.

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References

Bolda, J.: 2008, "Rapid Prototyping: A Sustainable Design Aid", REU research paper, Milwaukee School of Engineering.

Bourgeois, D.; Reinhart, C. F. and Ward, G.: 2008, A Standard Daylight Coefficient Model for Dynamic Daylighting Simulations, *Building Research & Information*, **36**(1), 68–82.

Crawley, D. B., Pedersen, C. O., Lawrie, L. K. and Winkelman, F. C.: 2000, EnergyPlus: Energy Simulation Program, *ASHRAE Journal*, **42**(4), 49–56.

Doelling, M. and Nasrollahi, F.: 2012, Building Performance Modeling in Non-Simplified Architectural Design, *Proceedings of the 30th eCAADe Conference*, Prague, 97–106.

Hetherington, R., Laney, R., Peake, S. and Oldham, D.: 2011, Integrated Building Design, Information and Simulation Modeling: The Need for a New Hierarchy, *Proceedings of Building Simulation 2011*, Sydney, 2241–2248.

Jakubiec, J. A. and Reinhart, C. F.: 2011, DIVA 2.0: Integrating Daylight and Thermal Simulations using Rhinoceros 3D, Daysim and EnergyPlus, *Proceedings of Building Simulation 2011*, Sydney, 2202–2209.

Mahdavi, A.: 2011, The Human Dimension of Building Performance Simulation, *Proceedings of Building Simulation 2011*, Sydney, K16–K33.

Moon, K.: 2005, *Modeling Messages: The Architect and the Model*, The Monacelli Press, New York.

Nabil, A. and Mardaljevic, J.: 2006, Useful Daylight Illuminances: A Replacement for Daylight Factors, *Energy and Buildings*, **38**(7), 905–913.

Reinhart, C. F.: 2006, *Tutorial on the Use of Daysim Simulations for Sustainable Design*, Institute for Research in Construction, Ottawa.

Rae, M. S.: 2000, *The IESNA Lighting Handbook. Reference & Application, 9th Edition*, IESNA, New York.

Reinhart, C.F. and Wienold, J.: 2010, The Daylighting Dashboard – A Simulation-Based Design Analysis for Daylit Spaces, *Building and Environment*, **45**(8), 2440–2457.

Sass, L. and Oxman, R.: 2006, Materializing design: the implications of rapid prototyping in digital design, *Design Studies*, **27**(3), 325–355.

Venancio, R., Pedrini, A., van der Linden, A. C., van den Ham, E., and Stouffs, R.: 2011, Think Designerly! Using Multiple Simulation Tools to Solve Architectural Dilemmas, *Proceedings of Building Simulation 2011*, Sydney, 522–529.

Wilcox, S. and Marion, W.: 2008, *User Manual for TMY3 Data Sets*, Golden, National Renewable Energy Laboratory.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 169–178. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

COMPUTATIONAL FLUID DYNAMICS FOR ARCHITECTURAL DESIGN

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Abstract. Computational fluid dynamics (CFD) is a cost-effective, well-known technique widely employed in industrial design. While indoor analysis can be achieved via CFD, wind tunnel testing (WTT) is still the prevailing mode of analysis for outdoor studies. WTT is often only performed a few times during the course of a building design/construction cycle and primarily for verification purposes. This paper presents a cross-disciplinary research initiative aiming to make CFD understandable and accessible to the architecture community. Our particular interest is in the incorporation of CFD into the early stages of architectural design. Many critical decisions, including those pertaining to building performance, are made during these stages, and we believe access to wind/airflow information during these stages will help architects make responsible design decisions. As a first step, we designed a passive cooling canopy for a bus stop based on the equatorial climatic conditions of Singapore where wind/airflow was a driving factor for geometry generation. We discuss our strategies for overcoming the two bottlenecks we identified when utilising CFD for this framework: mesh generation and result comprehension/visualisation.

Keywords. CFD; Simulation; visualization; concept design.

1. Introduction

Understanding natural phenomena in relation to buildings, particularly internal and external airflows, is becoming increasingly important to architectural design. This is due to the increased complexity of contemporary buildings and a growing interest in improving building performance in terms of the environmental impact.

2. Computational fluid dynamics in the building industry

Computational fluid dynamics (CFD) is a branch of fluid mechanics that utilises numerical methods to solve and analyse problems involving fluid flows. CFD has been commercially available since the early 1980s in the engineering community for applications such as turbo machinery, aerospace, combustion, and mechanical engineering. Today, CFD has proven to be a driving factor for performance enhancement in areas as diverse as Formula 1 racing, naval architecture for the America's Cup, and product development for swimwear; it has grown into an industry worth approximately 800 million dollars annually (Hanna, 2012).

During the past decade, CFD has been studied intensively in the domain of building environments. While the use of CFD for indoor applications is becoming established, further research is required for outdoor analysis (Blocken et al., 2009). Recent studies on the use of CFD for outdoor environments include simulation of pedestrian wind comfort (e.g. Mochida and Lun, 2008; Tominaga et al., 2008; Blocken et al., 2012), urban air pollution (e.g. Yang and Shao, 2008; Balczo et al., 2009; Tominiga and Stathopoulos, 2011), wind-driven rain (e.g. Huang and Li, 2010; van Hooff et al., 2011), and building surface heat transfer (e.g. Blocken et al., 2009; Defraeye et al., 2011; Karava et al., 2011). These studies and works focused on developing accurate and reliable simulation models and techniques or improving the design of relatively simple geometries with a few formal parameters.

Wind tunnel testing (WTT) remains the prevailing mode of analysis for outdoor studies in the building industry (Blocken et al., 2011). It is often performed only a few times during the course of a building design/construction cycle, if at all, for verification purposes. These tests are performed by wind/environmental consultants during the design development phase, and the impact of the gathered information on design is generally very limited.

The CFD versus WTT debate has been around since the introduction of CFD several decades ago; both methods provide a certain degree of knowledge and understanding of the environment in which the design exists. WTT requires an expensive setup and sophisticated instruments to measure field variables (wind velocity, pressure loads, turbulence intensity, and temperature). Its main limitation is that these measurements are obtained at only a few discrete points within the test section, which severely restricts understanding of the evolutionary or transient processes of unsteady complex phenomena such as vortex shedding, turbulence wakes, thermal stratification, and atmospheric boundary layer effects on the urban landscape.

CFD intrinsically overcomes this fundamental issue associated with WTT as the simulations yield instantaneous volume data. However, it suffers inherently from the discretisation of the governing equations of fluid dynamics – the Navier–Stokes equations for incompressible fluid flows – combined with model-

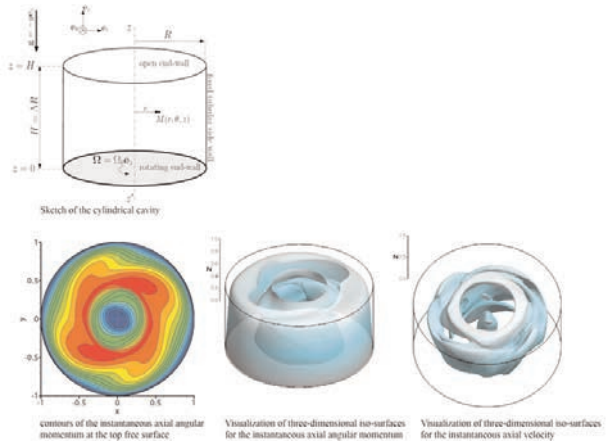

Figure 1. Use of CFD in engineering design. Simulation of an open transitional swirling flow (Bouffanais and Lo Jacono, 2009).

ling of the initial and boundary conditions. Some flow phenomena exhibit an extreme sensitivity to these conditions, often referred to as the 'butterfly effect' – this effect can dominate flow dynamics, particularly at large Reynolds numbers where convective instabilities strongly affect the flow dynamics. These current limitations to using CFD are often misinterpreted as a major hurdle to its adoption as a standard practice in many industries. Even so, CFD is used successfully in the aerospace, automotive, and many product design industries (Figure 1); this fact alone stresses the compelling possibilities for the use of CFD in architectural design. However, little research has been done on the use of CFD in relation with the architectural design process, specifically in the early stages when many critical decisions, including those pertaining to the building performance are made (Bogenstätter, 2000; Bazjanac et al., 2011). We believe that access to the wind/airflow information during these early stages will assist architects in making responsible and fact-assisted design decisions.

3. ARCH-CFD: Case Study Context

In this context, ARCH-CFD was set up as a cross-disciplinary research initiative the International Design Centre established by the Singapore University of Technology and Design and the Massachusetts Institute of Technology (MIT), with the aim of making CFD understandable and accessible to the architecture community at large. The objective of this research initiative is not to extend knowledge in the field of CFD but to find ways of utilising CFD to support early

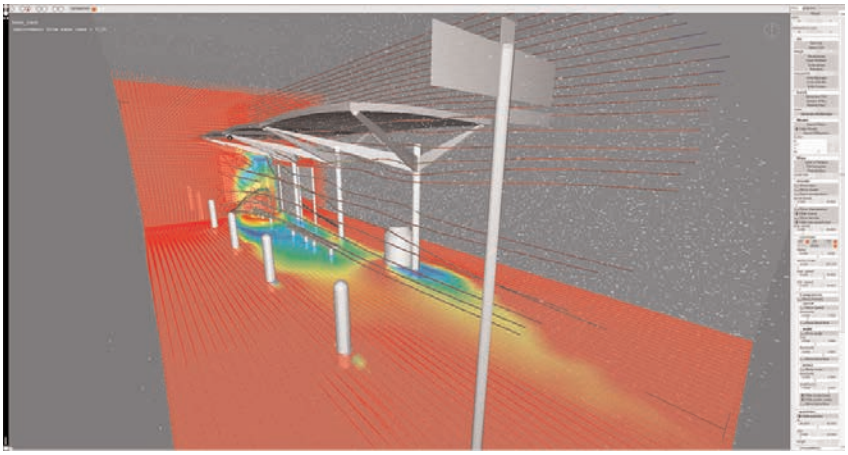

Figure 2. CFD analysis and flow visualization of an existing bus stop design using our in-house custom-developed visualization toolkit.

stages of the architectural design process in synthesising the complex phenomenon of airflow along with its usually complex dynamics. As a first step, a passive cooling canopy for a bus stop was designed based on the equatorial climatic conditions of Singapore where wind/airflow was the main driving factor for geometry generation. The typical bus stop geometry found in Singapore was used as a benchmark for measuring the improvements of our design (Figure 2). Improvements were assessed visually and measured quantitatively based on probability density distribution of wind speeds and the Predicted Percentage Dissatisfied (PPD) (Zhai, 2006) and Thermal Sensation (TS) (Cheng, 2010). The NURBS modelling software Rhinoceros was used for architectural modelling, whereas ANSYS FLUENT was used for the CFD analysis part. Here, we discuss two bottlenecks identified when utilising CFD in this framework: mesh generation and result comprehension.

3.1. MESH GENERATION

Computer simulations involve modelling the reality of something as an abstraction to facilitate understanding towards a specific aspect of interest. As architects and engineers look into different aspects of reality, the models they develop and manipulate are not directly interchangeable. For instance, architects develop three-dimensional models with the aim of developing visual accuracy when communicating spatial qualities that often include mixtures of lines, surfaces, and solids. On the other hand, CFD practitioners' primary goal is to obtain numerically

accurate analysis results, and common commercial tools require watertight solids as an input geometry.

Running CFD requires the creation of a volumetric meshing of the geometry of interest and its surroundings. This step is critical and is often the most labour-intensive. During the conceptual design phase, architects explore multiple geometries before arriving at a particular building design; this means that multiple meshing processes are required for repetitive runs of the CFD solver. Two aspects need to be balanced when meshing: quality and size. Mesh quality affects the overall accuracy of the analysis, while the mesh size – measured by the number of mesh nodes – dictates the overall computational cost, which can easily become overwhelming for complex geometries with extremely fine details.

At the current state of technology, architectural and engineering models are not interchangeable and require a significant amount of preprocessing for a simple standard conversion from one type to the other; a seamless conversion procedure is unfortunately still out of reach. Moreover, it is difficult to generalise a balancing strategy between simplification of geometry and accuracy of analysis. Typically, architects require quantity and speed rather than engineering accuracy from analysis in the early stages of design to explore multiple geometric options for compare and contrast. However, it is difficult for CFD practitioners to compromise on the accuracy as this could easily generate what they refer to as an 'untrusted' analysis.

In ARCH-CFD for our bus stop canopy case study, a hybrid mesh generation was employed to maintain an acceptable accuracy level while providing us with the flexibility of meshing various complex shapes and fine geometrical details (Figure 3). A hybrid mesh is the combination of a structured mesh (the outer surrounding environment) and an unstructured one (centred about the inner element of interest, i.e. the bus stop in our particular case of interest).

Historically, most computational methods were developed based on structured meshes, which, in general, are generated effortlessly. This is particularly true when boundaries have a simply geometry. However, with the advent of more powerful computers, CFD practitioners started simulating more complex flows and geometries for which structured meshes are commonly computationally prohibitive.

Unstructured meshes have gained popularity in recent years as an alternative approach for analysing flow dynamics involving complex geometries. Using an unstructured mesh offers two main advantages over traditional structured mesh. First, by not requiring the mesh to be logically rectangular, unstructured meshes offer considerable flexibility in discretising complex domains like the one we have, given the level of details of our bus stop. Second, and maybe of more importance in the framework of the ARCH-CFD project, unstructured meshes offer control of mesh density and stretching in a more flexible manner, which dramatically reduces the computational overheads. It is worth noting that those clear

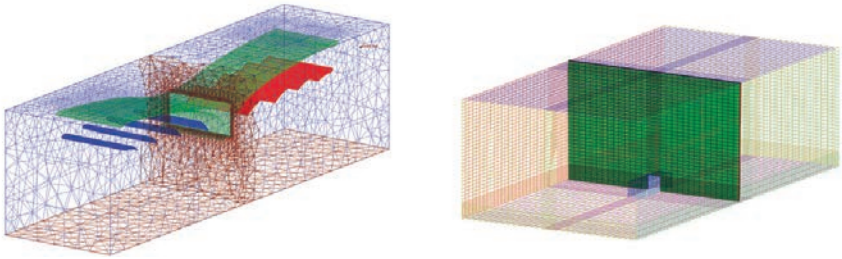

Figure 3. Hybrid mesh developed and used. Left: Inner unstructured mesh using tetrahedral cells around the geometry of interest (bus stop). Right: Outer structured mesh of the surrounding environment using quadrilateral cells.

advantages come at a cost in terms of numerical accuracy. Thus our hybrid mesh strategy – using a coarse structured mesh in regions with limited geometrical complexity and an unstructured one near the bus stop – allows us to achieve a good trade-off between simulation accuracy and computational cost. More specifically, such a hybrid meshing strategy enables simple and rapid iteration of a particular conceptual design while maintaining a reduced level of mesh cells; this increases efficiency without increasing the computing cost.

Here, a parametric model for geometry generation was developed; this model omitted details such as small holes, fillets, and sharp corners that are small in relation to the overall domain size. While these details may be important from the standpoint of architectural expression, they have very little effect on the overall airflow. The parametric model ensured consistency of the model for data exchange from design to analysis and was used by the architects as a means to improve communication with the engineers regarding the range of geometries under consideration. However, towards the end of the design, we omitted the parametric model in order for architects to control the geometry without any parametric restrictions.

3.2. RESULT COMPREHENSION

Once a proper mesh has been generated and the CFD solver has completed its run, the next state, which is of paramount importance, is to be able to fully comprehend and appreciate the results obtained from the CFD analysis. Most architects are usually not familiar with CFD, so it is difficult for them to observe images provided by CFD practitioners and expand their understanding of wind/airflow.

To make CFD results more intuitive and amenable to architects, an interactive visualisation toolkit, originally developed by Kaijima and Michalatos in 2009, was adopted and further developed for this case study. The toolkit takes

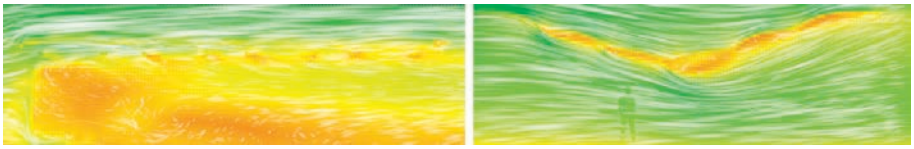

Figure 4. Sectional visualization of thermal sensation. Left: Existing bus stop design commonly encountered in Singapore. Right: Proposed bus stop design. The color map associated with the thermal discomfort goes from yellow to red; i.e. orange/red colors indicate areas of relative discomfort. TS= 0.1895TA-0.7754WS + 0:0028SR + 0:1953HR- 8.23 (Cheng, 2010) where TA = dry bulb air temperature, WS = wind speed, SR = solar radiation intensity, and HR absolute humidity.

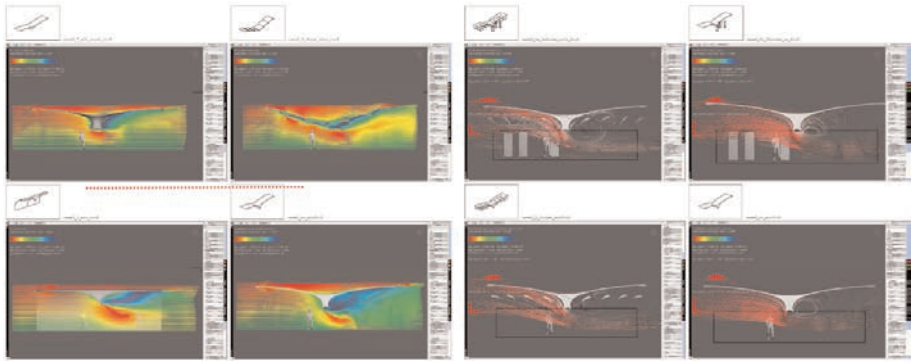

Figure 5. Examples of Design iterations. Screen Captures of the visualization toolkit.

Rhinoceros models and ANSYS analysis results in an ASCII text format containing positions, wind velocity field (*x*-, *y*-, and *z*-components), and the turbulence kinetic energy field. The toolkit offers interactive 3-D visualisations of physical phenomena throughout the domain of interest by creating a voxel data structure from a hybrid mesh structure. The discrepancy between the ANSYS results and the custom toolkit visualisations is controlled by the voxel size to be unperceivable. In addition to the more typical streamlines or sectional visualisations, capabilities to view thermal comfort (Figure 4) and vorticity (i.e. the curl of the fluid velocity field connected to the local rotational rate of particles of fluids) are incorporated along with animated steady Lagrangian particle tracking to aid the user in appreciating and understanding the often counterintuitive airflow features throughout the entire domain (Figure 5).

The toolkit helped not only the architects but also the engineers in grasping the flow field in relation to the architecture geometry; overall, it greatly improved

communication among the team, which ultimately resulted in an enhanced and improved design (Figures 6, 7). The details of quantitative as well as qualitative assessment method will be discussed in our future publications.

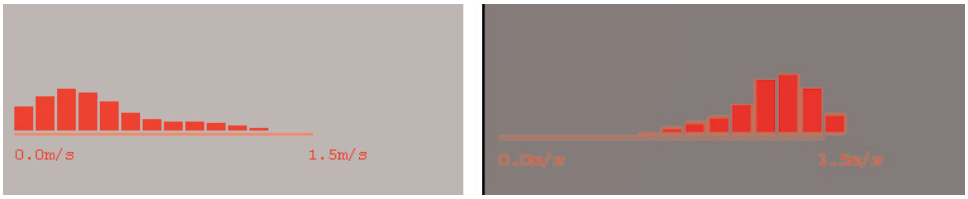

Figure 6. Probability Density Distribution of Wind speed. Left: Existing bus stop design commonly encountered in Singapore. Right: Proposed bus stop design.

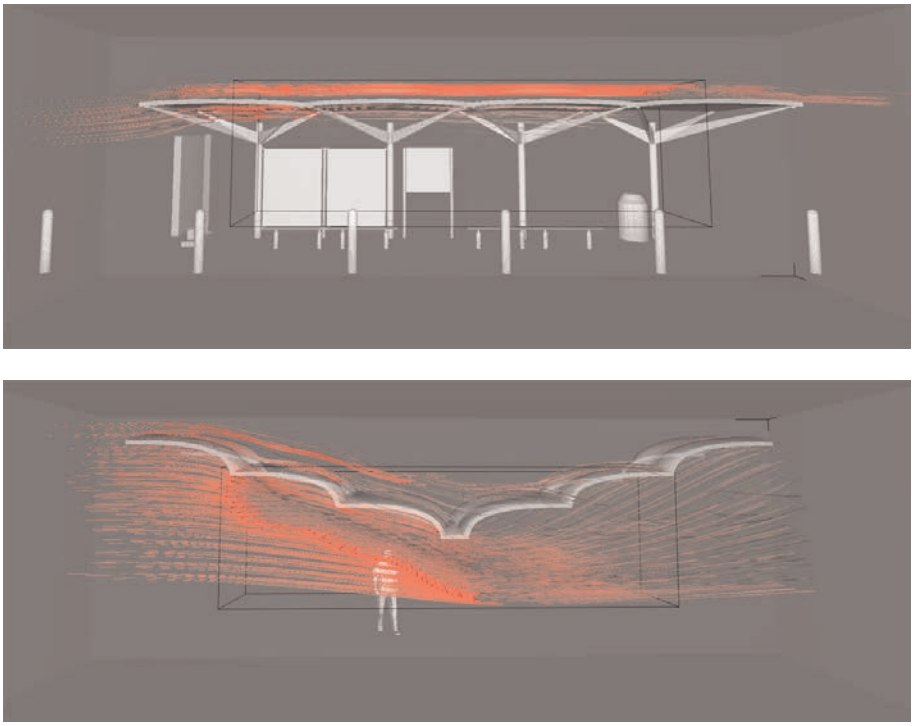

Figure 7. Visualization of a CFD analysis result using custom developed toolkit: Visualization of wind flow above 1.3 m/s coming into the space of interest. Top: Existing bus stop design commonly encountered in Singapore. Bottom: Proposed bus stop design.

4. Conclusions and Outlook

Computer simulations such as CFD have opened up new possibilities for design and research by introducing environments in which we can manipulate and observe. However, using such simulation tools in a meaningful manner is not a straightforward or easy task. The aim of the bus stop canopy case study project was to build a platform that would facilitate domain knowledge exchanges within the existing framework as a first step.

While visualisation helped both parties – the architects and the engineers – in communicating and documenting the process, the meshing remained fairly time-consuming even for such a small case study project. Our strategy of using a hybrid mesh reduced the number of nodes to approximately 4% of the original unstructured mesh, yet the initial setup seems infeasible in a larger context. As the next step, we plan to use meshless CFD methods to improve the interoperability between the two domains and to simply eliminate one of the two bottlenecks mentioned above.

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References

Balczo, M., Gromke, C. and Ruck, B.: 2009, Numerical modelling of flow and pollutant dispersion in street canyons with tree planting, *Meteorol. Z.*, **18**(2), 197–206.

Bazjanac, V., Maile, T., Rose, C., O'Donnell, J. and Mrazovic, N.: 2011, An assessment of the use of Building Energy Performance Simulation in early design, *Proceedings of Building Simulation 2011*, Sydney, Australia, 1579–1585.

Blocken, B., Stathopoulos, T., Carmeliet, J. and Hensen, J.: 2009, Application of CFD in Building Performance Simulation for the outdoor environment, *Eleventh International IBPSA Conference*, Glasgow, Scotland, 489–496.

Blocken, B., Stathopoulos T., Carmeliet, J. and Hensen, J. L. M.: 2011, Application of CFD in building performance simulation for the outdoor environment: an overview. *J. Building Perform. Simul.*, **4**(2), 157–184.

Blocken, B., Defraeye, T., Derome, D. and Carmeliet, J.: 2009, High-resolution CFD simulations of forced convective heat transfer coefficients at the facade of a low-rise building, *Build. Environ.*, **44**(12), 2396–2412.

Blocken, B., Janssen, W. D. and Hooff, T.: 2012, CFD simulation for pedestrian wind comfort and wind safety in urban areas: General decision framework and case study for the Eindhoven University campus, *Environmental Modelling & Software*, **30**, 15–34

Bogenstätter, U.: 2000, Prediction and optimization of life-cycle costs in early design', *Building Research & Information*, **28**(9), 376–386.

Bouffanais, R. and Lo Jacono, D.: 2009, Unsteady transitional swirling flow in the presence of a moving free surface. *Phys. Fluids.*, 21(6), 064107-1–064107-14.

Chen, Q. Y.: 2004, Using computational tools to factor wind into architectural environment design, *Energy and Buildings*, **36**, 1197–1209.

Cheng, V., Ng, E., Chan, C. and Givoni, B.: 2010, Outdoor thermal comfort study in sub-tropical climate: a longitudinal study based in Hong Kong, *Int. J Biometeorol*, **56**(1), 43–56.

Defraeye, T., Blocken, B. and Carmeliet, J.: 2011, Convective heat transfer coefficients for exterior building surfaces: Existing correlations and CFD modelling, *Energy Convers. Manage.*, **52**(1), 512–522.

Hanna, K. R.: 2012, CFD in Sport – Retrospective 1 1992-2012, 9th Conference of the International Sports Engineering Association (ISEA), *Procedia Engineering*, **34**, 622–627.

Huang, S. H. and Li, Q. S.: 2010, Numerical simulations of wind-driven rain on building envelopes based on Eulerian multiphase model, *J. Wind Eng. Ind. Aerodyn.*, **98**(12), 843–857

Jakeman, A. J., Letcher, R. A. and Norton, J. P.: 2006, Ten iterative steps in development and evaluation of environmental models, *Environmental Modelling & Software*, **21** (5), 602–614.

Karava, P., Jubayer, C. M. and Savory, E.: 2011, Numerical modelling of forced convective heat transfer from the inclined windward roof of an isolated low-rise building with application to Photovoltaic/Thermal systems, *Appl. Therm. Eng*., **31**(11–12), 1950–1963.

Mochida, A. and Lun, I. Y. F.: 2008, Prediction of wind environment and thermal comfort at pedestrian level in urban area, *Journal of Wind Engineering and Industrial Aerodynamics*, **96**(10–11), 1498–1527.

Tominaga, Y., Mochida, A., Yoshie, R., Kataoka, H., Nozu, T., Yoshikawa, M. and Shirasawa, T.: 2008, AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings, *J. Wind Eng. Ind. Aerodyn.*, **96**(10–11), 1749–1761.

Tominaga, Y. and Stathopoulos, T.: 2011, CFD modelling of pollution dispersion in a street canyon: comparison between LES and RANS, *J. Wind Eng. Ind. Aerodyn*., **81**(1–3), 273–282.

van Hooff, T., Blocken, B. and van Harten, M.: 2011, 3D CFD simulations of wind flow and wind-driven rain shelter in sports stadia: influence of stadium geometry, *Build. Environ*., **46**(1), 22–37.

Yang, Y. and Shao, Y.: 2008, Numerical simulations of flow and pollution dispersion in urban atmospheric boundary layers, *Environmental Modelling & Software*, **23**(7), 906–921.

Zhai, Z.: 2006, Application of Computational Fluid Dynamics in Building Design: Aspects and Trends, *Indoor and Built Environment*, **15**, 305–313.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 179–187. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

DOES THE DEBATE ON STRESS EFFECT LEAD EVACUATION SIMULATION MODELS TO DIFFERENT PERFORMANCES?

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Abstract. There exists a long time debate over the rational state of the evacuees in the evacuation simulation. Sime et al. insisted that the evacuees behave rationally in most cases. Following this argument Arthur and Passini concluded that if a setting works well under normal conditions, it will have a better chance of working well in emergency conditions. Such an argument for rational decision-making makes statistical models, such as utility maximizing model (UMM), acting as proper framework for choice modelling in evacuation. However, on the other side, some people pointed out that there exists panic in the evacuation and bounded rationality theory, represented by pruned decision tree model (DTM), should be adapted in choice modelling instead. Such a debate over stress effect causes hesitations and uncertainties when researchers try to select a proper model framework for their practical simulation. This study compared the performances (prediction accuracies) of the UMM and DTM with the same set of choice data collected in a virtual evacuation experiment. With a similar level of performance on both sides, it is suggested that the on-going debate does NOT bring any difference to the choice modelling in practical evacuation simulation. It is time to improve the performance rather than to continue the debate.

Keywords. Evacuation; architectural cue; machine learning; bounded rationality.

1. Introduction

One issue making the evacuation behaviour special from the other way-finding behaviour is evacuees' potential stress or even panic (Sun, 2009). People may behave differently in these emergent situations (Ozel, 1987). The differences in the stress levels lead to different extend of rationality when making decisions, which result in different modelling strategies (Maule and Svenson, 1993). Complete rationality models assumes that the decision maker has unlimited time, knowledge and computational

capacity to make decisions (Gigerenzer and Selten, 2002). Some even suggest if the decision-maker is ignorant about the current situation, they behave as if they knew of a probability distribution on states and ranked decisions using the criterion (Bouyssou et al., 2010). In this case, stress does not have any impact on the decision making process, which seems to be quite extreme and unnatural to most of us. Bounded rationality models, as appeared around 1950s (Simon, 1956), suggest that under time pressure and with resource limit, people usually make bounded rational decisions. In this case, stress has a prominent impact on the decision making process. The depth of thought is closely related to when the result is required, because in some situations, there might be a difference between life and death (Gigerenzer and Selten, 2002).

However, despite the debate between the both sides, there is no performance comparison between these decision making models in practical evacuation simulation, which is a typical environment under stress. In this research, two kinds of machine learning models (Witten et al., 2011, pp. 99–107) with complete and bounded rationality concerns respectively were trained using the same set of data from a virtual evacuation simulation. A third Neural Network Model (NNM) was also involved in the comparison as a reference because of its nature as trying to provide the same feedback as what it learns. The comparison of the prediction accuracies could show if one of these three modelling approaches performs better in practical evacuation simulation. With such a comparison, this study suggests that current debate on stress effect does not result in any performance differences to the evacuation modelling and simulation.

2. Method

Two kinds of models, namely Utility Maximizing Model representing a complete rational choice assumption without stress effect and pruned Decision Tree Model representing bounded rational choice assumption with a certain stress level, are used as framework to model a same set of evacuation choice data. An extra Neural Network Model is also used as a reference framework without any assumption about rationality or stress effect (a black box). A comparison of their prediction performances is conducted to reveal the feasibility of each assumption and the advancement of each theory with different rational level and stress effect concerns.

2.1. MODELS TO COMPARE

2.1.1. Utility Maximizing Model representing rational decision without stress effect

The Utility Maximizing Model is one kind of linear regression model and uses a polynomial with fixed coefficients to approximate the data (Aleskerov et al., 2007).

It is based on the assumption that choice alternatives can be represented as bundles of attribute levels. Individuals are assumed to derive some utility from these attribute values, and combine these part-worth utilities into some overall measure of utility according to some simple algebraic rule (Arentze and Timmermans, 2000).

The UMM model assumes that the individuals make rational decisions and has enough resources to evaluate all the utilities of the alternatives (Taddei, 2012), which means stress impact is totally not taken into account. The model provides a satisfactory characterization of rational behaviour under certainty, but fails to do so under risk and under uncertainty (Harsanyi, 1990). Because of this nature, the stress state of the subjects will not be considered during the evacuation simulation. The popular logistic regression method was chosen for this comparison.

2.1.2. Pruned Decision Tree Model representing bounded rational decision with stress effect

A pruned decision tree is a decision support tool that uses a tree-like graph or model of decisions and their possible consequences, including chance event outcomes, resource costs, and utility (Rokach and Maimon, 2008). Decision trees help to specify the sequences of decisions that need to be made along with the resulting recommendation, which is a very popular means of expression of a decision making process. A pruned decision tree model has been widely used in the field that save and transform lives such as emergency medical diagnosis, and it performs surprisingly well. Furthermore, it is also psychologically plausible, assuming prediction and limited information search rather than fitting and optimization (Keller et al., 2010).

The result of the decision tree model is a series of IF-THEN rules which constitutes a tree-like structure. The hierarchy of the tree structure corresponds to a step-by-step decision making process of a human being. It uses a heuristic process to find the acceptable alternative within an acceptable time and cost, which constitutes a powerful theoretical approach that conceptualizes choices as outcomes of heuristics. It is used to describe the behaviour of an unaided human mind with bounded rationality (Gigerenzer et al., 1999). With this nature, a decision tree model with branches pruned to a certain level is able to model the choice mechanism in a certain stress state during evacuation. The widely used J48 method was selected for this comparison.

2.1.3. Neural Network Model as a reference

An artificial neural network is a learning algorithm that is inspired by the structure and functional aspects of biological neural networks. It is usually used to

model complex relationships between inputs and outputs, to find patterns in data. Multilayer Perceptron is one type of neural network that trains using back propagation. It consists of multiple layers of nodes in a directed graph, with each layer fully connected to the next one (Witten et al., 2011, pp. 1–21).

Though the underlying structure of a trained neural network model is not descriptive, it is capable to give similar feedbacks based on what it is learning. This means it could model a proper stress impact based on the training data even though we do not know the exact stress status of every single subject. It was used in other stress related tasks such as the feature analysis of speech under stress (Hansen and Womack, 1996). The classic Multilayer Perceptron was selected as a reference model.

2.2. EVACUATION DATA FROM EXPERIMENT

A previous experiment was conducted on a CAVE platform (Cave Automatic Virtual Environment where subjects are immersed in a VR system with 180 degree display) to collect subjects' egress direction choices in a set of virtual evacuation scenarios (Sun, 2009). Subjects were faced with a virtual underground environment as if they were trapped and wanted to escape. They were asked to choose their preferred exits in the scene with multiple doorway entrances. Several attributes of selected doorway entrance were collected when the subject made his/her choices among several alternatives. The distance from the doorway entrance to the observation point is defined as attribute D, while the width of the doorway entrance is defined as attribute W. The angle between the direction of the view direction and the doorway entrance is defined as attribute A1 (Sun et al., 2008). Through analysis of these collected data ("learning" in the fields of data mining), the relations between these attributes and the subjects' choices of the doorway entrances are expected to be identified. This could help to establish a decision making model to further predict how people make choices in similar architectural scenes in case of life and death.

To impose a certain level of stress on the subjects, they were asked to complete the evacuation choices as soon as possible for a higher score (Figure 1). Moreover they would hear a noisy alarming sound during the experiment. And they would notice a counting down timer in the view. All these strategies made the subjects strained through the experiment. Scenes with two to eight doorway entrances were experimented with 161 participants, and they are mostly undergraduate students from grade 1–3 (Figure 2).

After the experiment, the subjects' choices on the seven kinds of scenes (from 2 to 8 doorway entrances in a scene) were collected and the data sizes of all these scenes are different (Table 1).

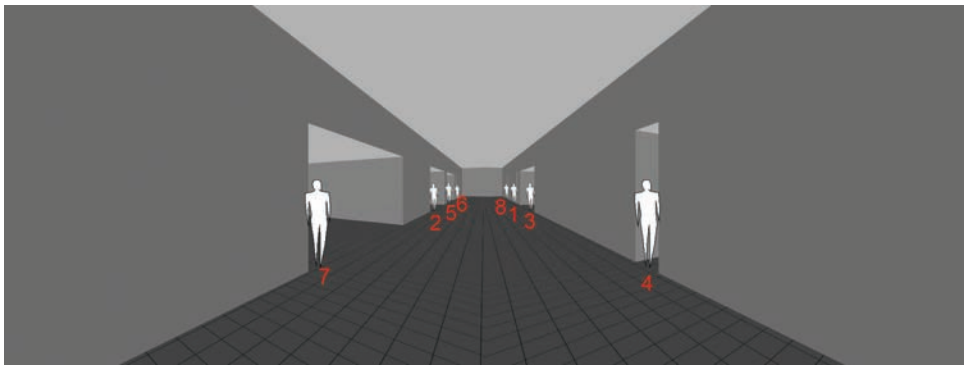


Figure 1. A scene with eight doorway entrances.

Figure 2. A virtual evacuation experiment on a CAVE platform.

Table 1. Data sizes of all the scenes with different number of doorway entrances (NDE).

	2 NDE	**3 NDE**	**4 NDE**	**5 NDE**	**6 NDE**	**7 NDE**	**8 NDE**
Data size	3572	5397	7068	8960	10764	4508	3920

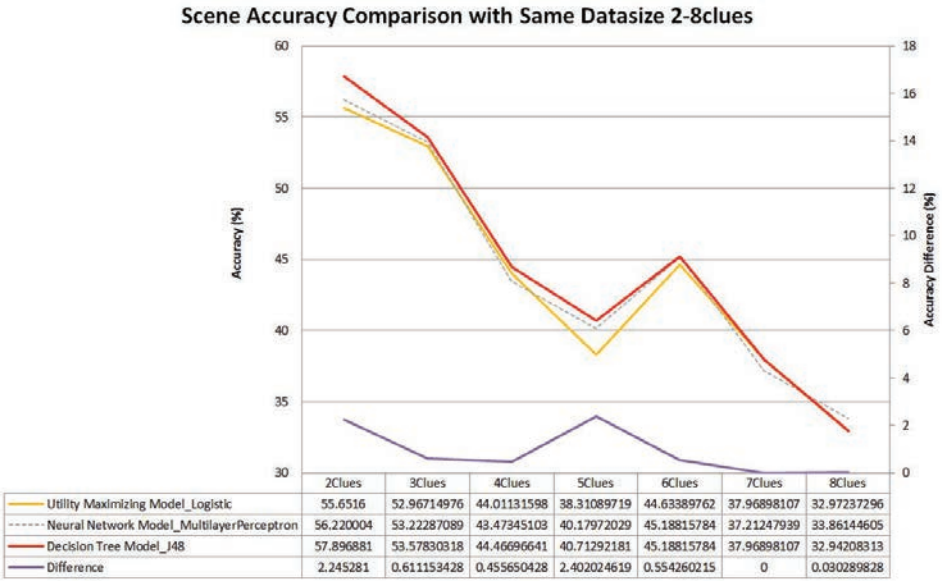
Table 2. A typical clip of the pre-processed data.

Std_D	Std_W	Abs_Std_A1S	SGN_A1S	Choice
1	0.125	0.16	-1	p
0.166667	1	1	1	u
0.166667	0.125	1	-1	u
0.666667	1	1	1	p
1	1	0.666667	1	u
0.666667	0.125	1	-1	u
1	1	0.16	1	u
0.666667	0.125	0.24	-1	u
0.166667	1	1	-1	p
0.166667	0.125	1	1	u

To achieve a better learning result, some pre-processing was done to all the collected data. The attribute values in one scene are standardized through the ratio of the value to the maximum value of this attribute appearing in the scene. Thus, the standardized attribute is always no more than 1. Besides the standardization of attribute D and W, attribute A1 has some extra pre-process, in which the abstract value of the attribute is used and its sign is split to form an extra attribute to indicate the side of the doorway entrance in the scene. Furthermore, any subjects' choice came in two states with "u" for unpicked and "p" for picked (Table 2).

2.3. DATA MINING AND PERFORMANCE COMPARISON

State of art data mining tools such as Weka could help to identify the relations between the attributes in the collected data and the subjects' choices of the doorway entrances with the aforementioned models (UMM, DTM and NNM). The prediction accuracies of the three models can be compared. To achieve an equal race condition for all the scenes with different number of doorway entrances, 1000 choices for each type of scene were randomly selected for the comparison. For the selected 1000 choices in each type of scene, 66.7% of the choices were collected randomly as the training data and the rest 33.3% choices were used to test the performance of these models. It is worth mentioning that the confidence factor of J48 is set to 25%, which allows for a moderate pruning of the decision tree and a good performance (lower the rate, the smaller the tree). The test results were transferred to excel through CSV files and a graph could be drawn to compare the prediction accuracies (Figure 3).



	2Clues	3Clues	4Clues	5Clues	6Clues	7Clues	8Clues
Utility Maximizing Model_Logistic	55.6516	52.96714976	44.01131598	38.31089719	44.63389762	37.96898107	32.97237296
Neural Network Model_MultilayerPerceptron	56.220004	53.22287089	43.47345103	40.17972029	45.18815784	37.21247939	33.86144605
Decision Tree Model_J48	57.896881	53.57830318	44.46696641	40.71292181	45.18815784	37.96898107	32.94208313
Difference	2.245281	0.611153428	0.455650428	2.402024619	0.554260215	0	0.030289828

Figure 3. The prediction accuracies of the three models in the seven types of scenes.

3. Results

According to the above comparison graph, the prediction accuracies, namely the performance, of three types of model framework are similar. They all descend as the number of doorway entrances in the scene increases from two to eight. Although the pruned Decision Tree Model appears always better than Utility Maximizing Model, the biggest difference between them is only about 2.4%.

As a conclusion, there's no significant performance difference between UMM representing a complete rational choice assumption without stress effect and pruned DTM representing bounded rational choice assumption with a certain stress level with complete rationality. Even a more general model, namely Neural Network Model, without any assumption about rationality level and stress effect has a similar performance. It suggests the choice behaviour researchers in practical evacuation simulation to improve the prediction accuracy whatever model framework he uses rather than following the debate on the stress effect in the future.

4. Discussion and Future Works

The prediction accuracy decreases as there are more clues exist in the scene. Will the prediction accuracy converge or continue to drop as the number of clues

increases? Furthermore, there exists an inflection point as number of doorway entrances is six for both utility maximizing model and decision tree model. This may due to the short term memory (STM) capacity of human beings, which is called a compound STM limits (Miller, 1956). Further experiments of scenes with more doorway entrances will be conducted and analysed together with the existing results. This may answer the questions raised here.

Acknowledgements

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References

Aleskerov, F., Monjardet, B. and Bouyssou, D.: 2007, *Utility maximization, choice and preference*, Springer.

Arentze, T. and Timmermans, H.: 2000, A learning based transportation oriented simulation system, *Transportation Research Part B: Methodological*, **38**(7), 613–633.

Arthur, P. and Passini, R.: 1992, *Wayfinding: People, signs, and architecture*, Focus Strategic Communications.

Bouyssou, D., Dubois, D., Prade, H. and Pirlot, M.: 2010, Decision Making Process: Concepts and Methods, Wiley.

Gigerenzer, G. and Selten, R.: 2002, *Bounded rationality: The adaptive toolbox*, MIT, Cambridge, MA, 38–48.

Gigerenzer, G., Todd, P. M. and ABC Research Group: 1999, Simple heuristics that make us smart, Oxford University.

Hansen, J. H. L. and Womack, B. D.: 1996, Feature analysis and neural network-based classification of speech under stress, *IEEE Transactions on Speech and Audio Processing*, **4**(4), 307–313.

Harsanyi, J. C.: 1990, Advances in understanding rational behavior, *in* P. K. Moser (ed.), *Rationality in Action: Contemporary Approaches*, Cambridge University, 271–293.

Keller, N., Cokely, E. T., Katsikopoulos, K. V. and Wegwarth, O.: 2010, Naturalistic heuristics for decision making, *Journal of Cognitive Engineering and Decision Making*, **4**(3), 256–274.

Maule, A. J. and Svenson, O.: 1993, *Time Pressure and Stress in Human Judgment and Decision Making*, Springer.

Miller, G. A. G.: 1956, The magical number seven plus or minus two: some limits on our capacity for processing information, *Psychological review*, **63**(2), 81–97.

Ozel, F.: 1987, *A computer model BGRAF: A cognitive approach to emergency egress simulation*, University of Michigan.

Rokach, L. and Maimon, O. Z.: 2008, *Data mining with decision trees: theory and applications*, World Scientific.

Sime, J. D.: 1980, The concept of panic, *Fires and human behaviour*, **1**(5).

Simon, H. A.: 1956, Rational choice and the structure of the environment, *Psychological review*, **63**(2), 129.

Sun, C.: 2009, *Architectural cue model in evacuation simulation for underground space design*, PhD Dissertation, Eindhoven University of Technology, Eindhoven, The Netherlands.

Sun, C., de Vries, B. and Zhao, Q.: 2008, Measure the Evacuees' Preference on Architectural Cues by CAVE, *in* H. J. P. Timmermans and B. de Vries (eds.), *Proceedings of the 9th International*

Conference on Design & Decision Support Systems in Architecture and Urban Planning, Eindhoven University of Technology, Eindhoven, The Netherlands, 15 pp.

Taddei, D.: 2012, *From Rational to Behavioral: New Tendencies in Decision Theory and Cognitive Psychology and their Impact on the Routine Level Analysis of Organizations*, PhD Dissertation, LUISS Guido Carli.

Witten, I. H., Frank, E. and Hall, M. A.: 2011, *Data Mining: Practical Machine Learning Tools and Techniques*, 3rd ed., Morgan Kaufmann.

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DAYLIGHTING AS A SYNTHESIS TOOL IN THE EARLY STAGE OF AN URBAN-SCAPE DESIGN

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Abstract. This paper proposes an integrated daylighting design framework for developing optimal configurations of multiple buildings in order to achieve satisfactory visual comfort level. The proposed approach consists of the application of *Climatic envelope* and Design Rules with assorted computational tools. The envelope becomes a prescriptive zoning tool and 3D boundary of parcel design that clarifies environmentally conscious design boundary for architects to develop various building configurations. Its synthetic implementation of natural light in the design process is combined with Design Rules for optimizing the building configurations to maximize their visual comfort level. The proposed design framework is demonstrated through a real site application; Honolulu, HI and Seattle, WA where two dominant sky conditions, clear and overcast sky, are represented. The integrated framework is introduced as a design guideline for architects to develop initial building configurations that maximizes the visual comfort in the early design stage.

Keywords. Daylight design; visual comfort; climatic envelope; design rules; urban-scape; design synthesis; configurations of buildings.

1. Introduction

Natural light is one of fundamental factors in environmental design to decide user's satisfaction with allowing basic human activities, creating spatial experience and revealing the form of a space. The replacement of electric light with the natural light in architectural design has been shown as one of the most effective ways for the reduction of energy use (DeKay, 2010, p. 36). According to International Energy Agency (IEA, 2000), current daylighting design practice is developed according to the growing need of environmental sustainability. Daylight becomes one of instrumental factors at the early stage of architectural

design process rather than just environmental analysis tool in the post evaluation process (Caldas, 2008; Rakha and Nassar, 2010).

However, the application of daylighting in the current design practice has been limited to investigate and develop a single building at a time. It hinders an overview of how buildings affect the quality of visual comfort to each other (Steffy, 2002). In his "Daylighting and Urban Form," Decay introduces the concept of *Climatic Envelope* that provides initial point of designing building configurations, allowing daylighting design as a synthesis tool to generate urban-scape (DeKay, 2010). Consequently, the study takes *Climatic Envelope* as the inception of the framework. Design rules are then developed to find optimal configurations of buildings regarding visual comfort illuminance level in specific sky and site condition with assorted computer applications such as SketchUp, Ecotect, and Designbuilder. Integrated design procedure introduces daylighting as a synthesis tool for generating urban-scape with optimal visual comfort level at the early design stage.

2. Daylighting Design Framework

Successful provision of natural light can be achieved through the interplay of natural light and building form (Reinhart and Galasiu, 2006). The proposed daylighting design framework is developed for maximizing visual comfort level in early architectural design of an urban-scape. It consists of *Climatic Envelope*, basic design rules, and procedures.

2.1. CLIMATIC ENVELOPE

Climatic Envelope (DeKay, 2010), the composite of solar and daylight envelope, deals with both direct sunlight and daylight for a full spectrum of natural light under both clear and overcast sky conditions.

Solar Envelope and *Daylight Envelope* are two representative theories regarding natural light in designing a building form. They are the product of latitude, built context, the size, shape, slope and orientation of the site. While *Solar Envelope* ensures the access of direct solar light to the site (Sarkar, 2009), *Daylight Envelope* assures adequate daylight access, ambient light to the street and adjacent buildings by shaping and spacing buildings (Brown and DeKay, 2001). In this paper, *Climatic Envelope* is employed as a 3D boundary to constrict the growth of height and width of the given site which limits building's volume growth as shown in Figure 1. Based on *Climatic Envelope* boundary condition, building volumes are adjusted. The volumes of segmented building blocks out of the boundary are reconfigured back into the building where the cut volumes came from as shown in Figure 7.

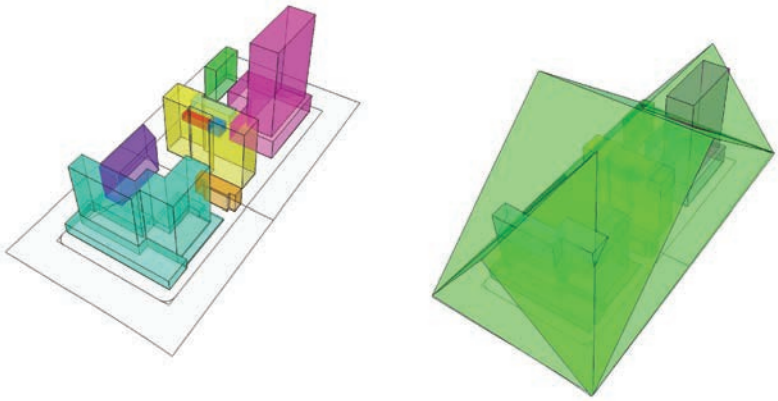

Figure 1. Climatic Envelope.

2.2. DESIGN RULES

According to "Daylighting Report" by Illuminating Engineering Society (IES, 2012), the implications of orientation, massing and building placement play a significant role in the effectiveness of daylighting. The design rules provide the guideline for orientation, form, size and placement of buildings in a given city block (Knowles, 1981) under clear and overcast sky conditions. These dominant sky conditions correspond to different natural lights; direct sunlight and daylight. While direct sun light exists under clear sky condition, daylight exists in overcast sky condition (Brown and DeKay, 2001, p. 110). Current daylighting standards including *LEED (Leadership in Energy and Environmental Design) 2002/ 2009 Indoor Environment Quality 8.1* regard sky conditions for all regions uniformly. However, as different angles of sun path impact the daylighting quality in buildings, sky conditions have significant influence to the building forms and their relations (Brown and DeKay, 2001). Therefore, lighting quality in these two sky conditions should pursue the provision of visual comfort which requires the satisfaction of the visual system and the absence of glare (Dubois, 2007, p. 8). The illuminance level for visual comfort generally ranges from 300 to 2000 lux for various tasks and avoiding glare (Advanced Buildings, 2012).

2.2.1. Orientation of Building Growth Pattern

The orientation of buildings is crucial to mitigate excessive solar access to interior environment (Knowles, 1981, p. 143). Under both clear and overcast sky conditions, the most preferred growth pattern of the buildings is EW (east-west) direction, which maximizes the southern exposure so that more diffused light can enter the inside of

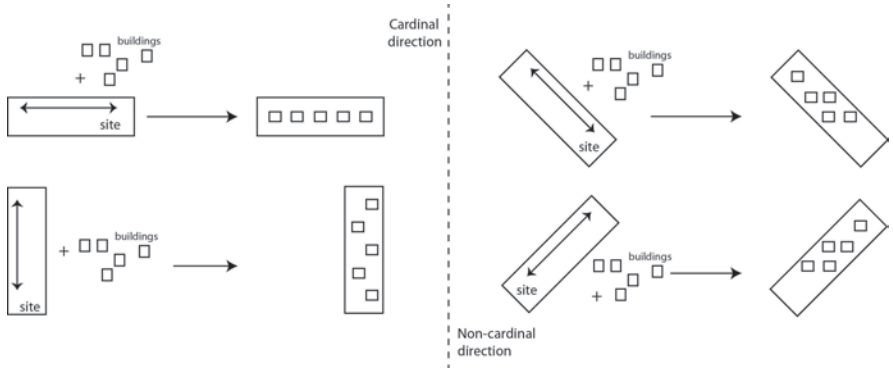

Figure 2. Buildings' general growth pattern per sites' orientation.

the building, and the potential for glare can be reduced (Hausladen et al., 2008). Depending on the given site's orientation, buildings should be situated properly. Since sunlight angle on the south facade is steep, the intensity of sun radiation is less comparing to other sides (Hausladen et al., 2008, p. 40). Therefore, maximization of the southern exposure of buildings is the key to design multiple buildings' growth pattern for minimizing the potential for glare. General growth pattern of buildings in both cardinal and non-cardinal site orientation is demonstrated in Figure 2.

2.2.2. Placements of Buildings

Although given site is sometimes in the situation with difficult natural light access, the juxtaposition of buildings can mitigate the effects of the natural variation of sunlight (Knowles, 1981, p. 144). For both clear and overcast sky conditions, EW cardinal layout creates potential for good visual comfort level.

The design rules for the placements of buildings under clear sky condition are: 1) when the buildings are located on EW growth, place short buildings on the west side, 2) when the buildings are situated in NS (north-south) cardinal growth, place short buildings on the north side, 3) if the site is oriented in NW-SE direction, short buildings should be placed on NW side, 4) short buildings are better to be placed on SW side when the buildings are non-cardinally oriented in NE-SW direction, 5) compact and closed configuration of buildings work better to achieve visual comfort illuminance level in clear sky condition because the buildings can be a shade to each other which lowers the potential for glare issues and direct sunlight, 6) When the building surfaces are overlapped, it is better to have tall building surfaces face either north or south, and 7) Specific building height difference and distance have direct relationship, d=x(h) where d=distance between buildings,

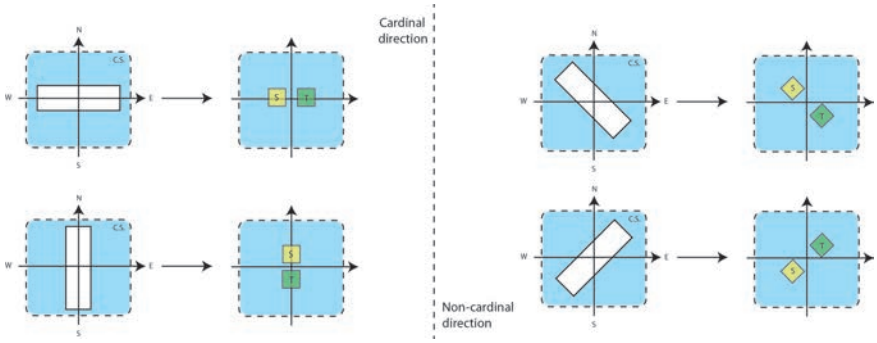

Figure 3. Basic Configurations of Buildings: Clear Sky condition.

h=building height and distance factor x=[0.8,1.3] (Brown and Dekay, 2001). Based on the illuminance level ranking under clear sky, the relationship of building placements in height difference is illustrated in Figure 3.

Also, the design rules for the placements of buildings under overcast sky condition are: 1) For cardinal direction, short buildings are better to be placed in the east side when the site is in EW growth, 2) When the site is in NS growth, short buildings should be placed in the south side, 3) building location with general height difference in non-cardinal site is same for both dominant sky conditions, 4) especially in winter time, non-overlap and open layout of the buildings is preferred to maximize the sun access to short buildings, and 5) For the direct relationship, d=x(h) where d=distance between buildings and h=building height, distance factor x is x=[2.5,5.4] under overcast sky condition. The summary of building placements based on relatively high visual comfort illuminance level under overcast sky is shown in Figure 4.

2.2.3. Building Forms

The form of building plays a significant role to control sunlight access (Rakha and Nassar, 2010). Transformation of the building is essential to establish better environmentally fit relationship among interrelated buildings around (Knowles, 1981, p. 145). Prototypical building forms for solar design are straight, angled and stepped forms (Brown and DeKay, 2001). Stepped building forms are preferred in overcast sky condition because stepped surfaces allow sunlight to be reflected off of front horizontal surfaces that can bring indirect and diffused light into interior spaces such as light shelf effect (Brown and DeKay, 2001). Angled building form is preferred in clear sky condition with 30 degree slope. However, the degree of building slope between 15 and 60 is acceptable for creating adequate visual comfort level. Preferable building forms under each dominant sky condition are shown in Figure 5.

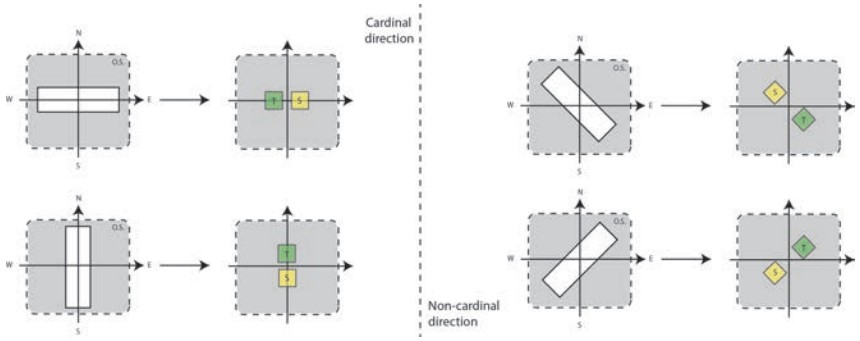

Figure 4. Basic Configurations of Buildings: Overcast Sky condition.

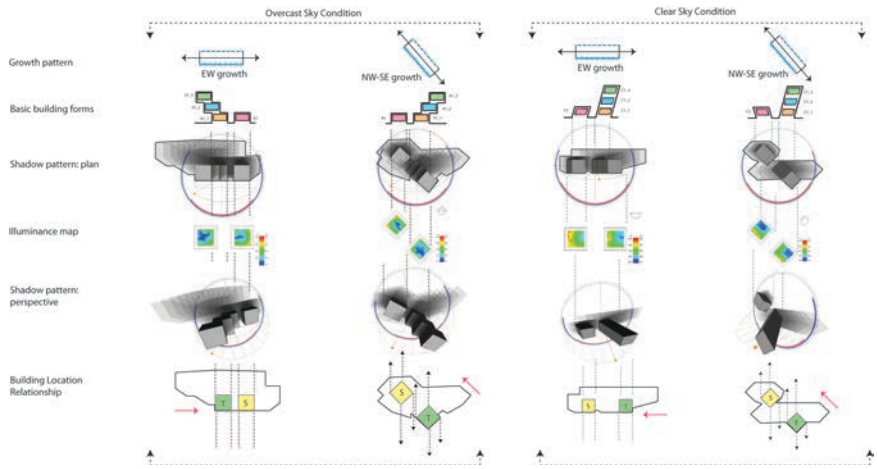

Figure 5. Building forms: Overcast Sky and Clear Sky condition.

2.3. PROCEDURE

This proposed framework requires four procedures as shown in Figure 6: 1) the application of *Climate Envelope*, 2) the decision on dominant sky condition, 3) the application of the Design Rules for the reconfigurations of alternatives, and 4) the design iteration if average visual comfort is not satisfied.

Considering latitude, dimension and orientation of the given site, *Climatic Envelope* is constructed over the target site lot. When the envelope is constructed, a part of existing buildings are cut off by the envelope's 3D boundary condition in SketchUp. Dominant sky condition of the given site is determined according to the geographical location of the site with the help of Ecotect, a sustainable building

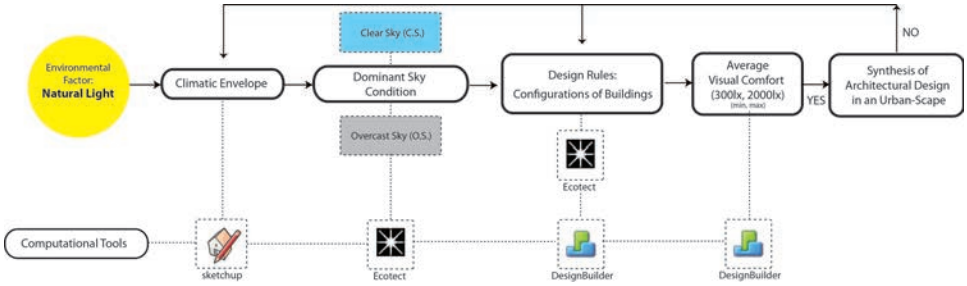

Figure 6. Framework: Synthetic Design Sequence with Natural Light in an Urban-Scape.

design software that offers analysis for daylighting and shadow patterns. Based on the sky condition, designer would choose appropriate design rules for the site prior to synthesize configurations of buildings. Based on orientation of the site, placement buildings and building form in design rules, the cut building volumes from the result of *Climatic Envelope* are reconfigured. Reconfigured variations are transferred to DesignBuilder for verification of visual comfort levels. DesignBuilder is a software tool for checking building lighting and comfort performance. Through the procedures, Ecotect is employed for reviewing shadow patterns to understand the relationship among buildings' height and their distances relating to the illuminance results of target buildings. If the visual comfort level of the configuration does not reach closer to average visual comfort standard, the application of *Climatic Envelope* and the design rules of the reconfigurations of alternatives are repeated.

3. Case Study: Clear Sky Condition vs. Overcast Sky Condition

The proposed framework is applied to the urban block design of two selected sites under clear and overcast sky condition. The chosen project city block is in Honolulu, Hawaii where 74% of the year is in clear sky condition. This same city block is applied in the latitude and weather condition of Seattle, Washington where 81% of a year is under overcast sky condition. The buildings in this site are conventional rectangular forms with various heights and volumes. Existing building layout is relatively closed form. Once Climatic Envelope is applied, the site is gone through the investigation of 1) orientation of building growth pattern, 2) placements of buildings and 3) building forms. Lastly, variation results are compared and analyzed to verify the application of *Climatic Envelope* and Design Rules in real site. Also, the illuminance resulted from the comparison between segmented building blocks and building as a whole clearly shows that a building's size affects the relationship between buildings' exposed surfaces and their volume

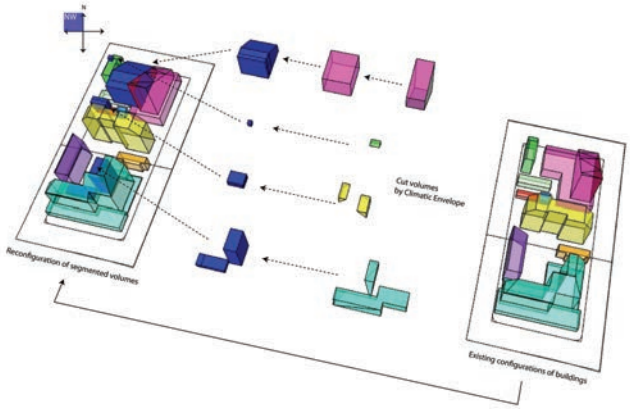

Figure 7. Reconfiguration of segmented volumes.

(Knowles, 1981, p. 145). Segmented buildings provide better opportunity for visual comfort lighting than one big mass building because of a reduced susceptibility of large buildings to external variations (Knowles, 1981). The speed of response to environmental change is much slower in large buildings than smaller buildings. Placement of segmented building blocks based on Design Rules is exemplified in Figure 7. The illuminance level differences from building size and volume changes are demonstrated in following case studies.

3.1. CLEAR SKY CONDITION

Application of *Climatic Envelope* and Design Rules provide significant reduction on building's high illuminance level by reconfiguring big building mass into smaller building sizes.

As shown in Figure 8, in the case of comparing illuminance level of existing site (min: 1701 lx, max: 4267 lx) to the illuminance level of *Climatic Envelope* applied site (min: 1285 lx, max: 3594 lx), the latter has gotten much closer to average visual comfort standard (min: 300 lx, max: 2000 lx).

3.2. OVERCAST SKY CONDITION

Overall average illuminance level in overcast sky condition is relatively lower than the illuminance level in clear sky condition because it deals with ambient natural light than direct sunlight.

The illuminance level from existing site (min: 1408 lx, max: 3899 lx) is still very higher than any other variations. When the building forms are modified to stepped

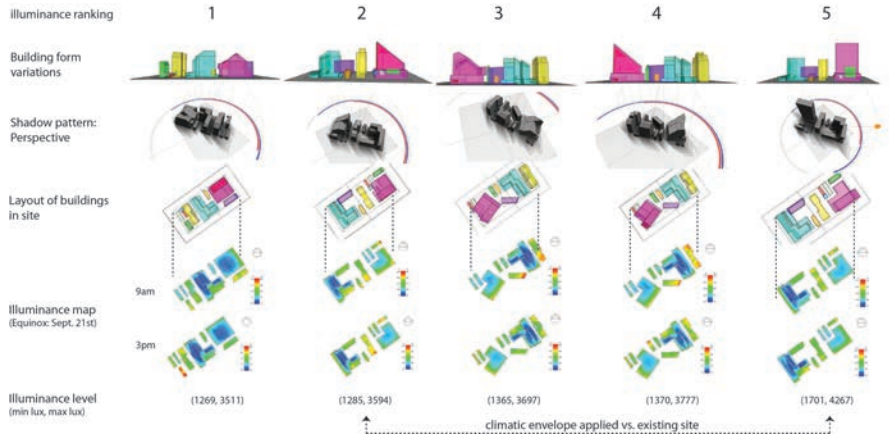

Figure 8. Illuminance Ranking: Clear Sky Condition, Honolulu, HI.

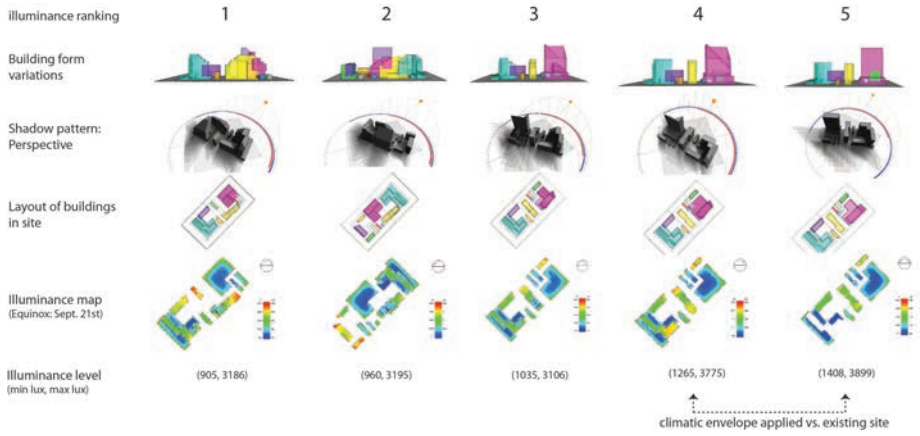

Figure 9. Illuminance Ranking: Overcast Sky Condition, Seattle, WA.

building forms such as building form variation #1, the illuminance levels of the variations has gotten much closer to visual comfort standard as shown in Figure 9.

4. Conclusion

In this paper, a synthesis-based environmental design framework based upon natural light is proposed for optimal visual comfort level at the early stage of an urban-scape design. The proposed framework includes 1) the implementation of

Climatic Envelope as a 3D boundary of buildings in a given site, 2) basic Design Rules under clear and overcast sky conditions of the site and 3) procedures for integrating *Climatic Envelope* and the Design Rules. In this study, the daylighting performance of building is introduced as a synthesis tool for the design of an urban-scape in order to maximize its visual comfort. Furthermore, the framework has expanded the application of daylighting to the design of multiple building relations with enhancing visual comfort level from single building-focused daylighting analysis. The results of the case studies under two dominant sky conditions show that the proposed design framework allows a user to achieve significant increase of visual comfort level of the multiple buildings in the selected sites. This paper presents how architectural design can initiate the design process with daylighting as the key design driving factor. The further study will include the development of parametric modeling application based upon the design rules in order to generate various urban-scape configurations and find an optimized configuration.

References

Advanced Buildings: 2012, "Daylighting Pattern Guide". Available from: <http://patternguide.advancedbuildings.net/> (accessed on 13 October 2012).

Brown G. Z. and DeKay, M.: 2001, *Sun, Wind and Light: Architectural Design Strategies*, 2nd ed., John Wiley, New York.

Caldas, L.: 2008, Generation of energy-efficient architecture solutions applying Gene_Arch: An Evolution-based generative design system, *Advanced Engineering Informatics*, **22**(1), 59–70.

Dekay, M.: 2010, Daylighting and Urban Form: An Urban Fabric of Light, *Journal of Architectural and Planning Research*, **27**(1), 35–56.

Dubois, C.: 2007, The Influence of Daylighting on Occupants; Comfort and Diversity of Luminous Ambiences in Architecture, *Solar 2007*, American Solar Energy Society, 720–725.

Hausladen, G., de Saldanha, M. and Liedl, P.: 2008, *ClimateSkin, Building-skin Concepts that Can Do More with Less Energy*, Birkhäuser, Basel.

IEA (International Energy Agency): 2000, Daylight in Building Design, in Ø. Aschehoug, J. Christoffersen, R. Jakobiak, K. Johnsen, E. Lee, N. Ruck and S. Selkowitz (eds.), *Daylight in Buildings: A source book for daylighting systems and components*, Lawrence Berkeley National Laboratory, Berkeley, CA, 2-1–2-20.

IES (Illuminating Engineering Society): 2012, "ZECBC: Public Policy Daylighting Report". Available from: <www. ies. org> (accessed on 26 September 2012).

Knowles, R.: 1981, *Sun, Rhythm, Form*, The MIT, Cambridge, MA.

Park, H.-J.: 2008, Parametric variations of Palladio's Villa Rotonda, *International Journal of Architectural Computing*, **2**(6), 145–169.

Park, H.-J.: 2011, Mass-customization in the design of 4,000 bus stops, in Leclereq, P. et al. (eds.), *Proc. 14th CAAD Futures Conference*, Liège, 265–278.

Rakha, T. and Nassar, K.: 2010, *Daylight as an evolutionary architectural form finder*, Nottingham University.

Reinhart C. F. and Galasiu A.: 2006, Results of an Online Survey of the Role of Daylighting in Sustainable Design, NRC-IRC Report.

Sarkar, A.: 2009, Low Energy Urban Block: Morphology and planning guidelines, *45th ISOCARP Congress*, 1–10.

Steffy, G. R.: 2002, *Architectural Lighting Design*, 2nd ed., John Wiley, New York.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 199–208. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

USING GAME-LIKE NARRATIVE TO SIMULATE HUMAN BEHAVIOUR IN BUILT ENVIRONMENTS

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Abstract. Predicting future users' behaviour and their activities in a building is a highly complex task that designers have to face during the design process. Despite its importance, few methods exist that can predict and help evaluate this type of building performance during the design process itself. Simulative approaches are gradually overcoming this shortcoming, but at present their application is limited to the representation of specific occurrences and behavioural performance aspects, such as emergency egress. Based on current developments in the video game industry, our research aims to establish a new approach to human behaviour simulation in built environments, based on a clear and reliable representation of the use processes occurring in a building. At its core is simulation based on the notion of *events*, defined as active entities on their own, comprised of space, people, and activities. These events entities are structured into collections called *narratives*, which represent and allow the simulation of the step-by-step performing of activities by users in a built environment.

Keywords. Human behaviour simulation; building-user interaction; prediction and evaluation; event model; game narrative.

1. Predicting Users' Behaviour in Building Design

The building's ability to meet the needs of its users is one of the key factors in evaluating the quality of a proposed building design. Yet, predicting users' behaviour

in an environment that has not yet been built and evaluating the impact of such environment on their activities and interactions with other people, is a highly complicated task.

Despite its relevance, few methods exist that can predict and help to evaluate this type of building performance during the design process itself. One of the main causes for this shortage is the large amount of knowledge needed to do so, its dispersion among many fields of study (cognitive science, ergonomics, environmental psychology, social sciences, to mention just a few), and its difficulty of integration and formalization in reliable, computationally-accessible structures. Further increasing this complexity is the non-deterministic nature of human behaviour itself, which is heavily context-dependent (on such aspects as culture, education, role and dynamics in the society, customs, and beliefs), due to which every human being behaves very differently from others given the same event and same built context.

Human response to a built environment includes its perception, the ergonomics of its use, the impact of its intervention within human social systems, and its interpreted meaning (Kaplan and Kaplan, 1982). It is probably the most difficult aspect of performance to evaluate and predict before construction, but in the final analysis, it is the most important one because a successful human response is the essence of successful design (Steinfeld, 1992).

Currently, the most conventional way to implement knowledge about users and their behaviour in architectural design processes is by indirectly verifying the building's conformity to norms and regulations. They provide a unifying action of the different human factors' instances, but their high level of generalization makes them ill-suited to the intrinsic uniqueness and context-dependence of an architectural product. In addition, the dynamic and stochastic nature of human behaviour can hardly be covered by static, regulatory representations.

Lawson's statement, which affirms that "the best test of most designs is to wait and see how well they work in practice" (2006), describes the motivation of progressive introduction of simulative approaches to representing the interaction between human and environment. Simulation is considered to be the most valid method for evaluating the performance of designed artefacts when the relationships among the decision variables are too difficult to be established analytically, because they interact in complex ways or there are too many of them (Kalay, 2004).

With the exponential increase in computing power and the availability of new simulation approaches and paradigms, human-built environment interactions have begun to be introduced into building performance evaluations. They are gradually overcoming the shortcomings derived from the heretofore domination of normative approaches (Koutamanis and Mitossi, 1996), yet, at present, their real contribution is limited to the representation of specific occurrences and/or specific aspects of human behaviour (e.g. fire egress, route analysis, etc.).

In addition, one of the more innovative simulation paradigms – Agent-Based Modelling (ABM) – is showing its limitations when applied to simulating the complexity of user interactions with other human beings and with the built-environment. The ABM approach is geared toward representing human behaviour in buildings as the sum total of single, autonomous objective-driven behaviours of all the agents in relation to the context (built environment, other agents, etc.) surrounding them. This kind of approach gives reliable results when applied to behavioural aspects and specific occurrences characterized by high rate of individual action (i.e. escaping from fire in a building), but fails in simulation of real cooperation and collaboration among different agents (O'Sullivan and Haklay, 2000).

The aim of our research is to develop a new approach to simulating human behaviour in built environments, based on a clear and reliable representation of structured, collaborative behaviour, instead of the sum of arbitrary and individual behaviours of single agents. Our modelling approach is derived from developments in game narratives and at its core is simulation based on the notion of *events*, which we consider active entities on their own. Events are structured into collections called *narratives*, or scenarios, which represent the processes occurring in a building while it is in use. To validate the event-based modelling approach, a first implementation has been developed that deals with the representation of human behaviour in a hospital nursing ward.

2. Events and Scenarios

When we look at the phenomenon of users' behaviour in a built environment, what we see is a sequence of localized occurrences involving people and their system of actions/interactions. Sometimes these happenings are discrete in time and clearly distinguishable, sometimes they are prolonged and blurred. To reliably represent these occurrences, which we identify as central entities of our model, we need to judiciously combine three types of information: *what* are the Activities performed, *who* are the Actors involved, and *where* do they happen (the Spaces). These types of information cannot be simply grouped into structures, because they represent heterogeneous and independent domains of data and each of them acquires a specific meaning depending on its grouping into the assembly. In order to manage these structures of data we have developed the notion of *events*: an entity that provides a context that allows the specific combination of Actors, Spaces and Activities to be interpreted in a meaningful manner (Figure 1).

Derived by Heidegger's definition of *Ereignis* (1962), the concept of *event* is the dynamic representation of a discrete element of the building-in-use phenomenon. It is a phenomenological entity in which we can find a coexistence of abstract and real states of meanings. Its abstract meaning is "a characterization of change",

Figure 1. Events as intersection of Actors/Activities/Spaces domains.

a representation of the process of change of a (very small) part of the world's status and of the entities involved. It gets its own real meaning when it occurs, becoming a manifestation of that change.

When we look at events in real world building-in-use, they are a direct consequence of the goal-oriented behaviours of the actors within the built environment, of their interaction with what surrounds them and with other actors. This is very hard to represent computationally: it would require representing, for each actor, the complex cognitive and decision-making process, in real time, possibly in parallel for all the actors involved (Kalay and Irazabal, 1995). In addition, it is necessary to represent not just simple, individual behaviours (as in a fire egress simulation) but also interactions, cooperation and collaboration among different actors. It would be extremely unmanageable (if not impossible) to control all this complexity using an agent-based system: it would mean to build a very accurate set of behavioural rules for each agent and situation, in order to provide them the possibility to recognize other agents' actions and purposes, confront their own objectives and behaviour, and adapt their own actions.

Our approach circumvents this problem by assigning the perception-action process to the *events*, rather than the individual actors. Each event entity, which encompasses actors, spaces, furniture, and building components, is provided with an AI (artificial intelligence) engine and associated knowledge base, so that it is able to directly control its own action and the behaviour of the objects it comprises. This approach leverages the 'virtuality' of the simulation: while in physical world intelligence is the province of humans, in the virtual world of the computer

intelligence can be assigned to non-human entities, such as events. The advantage of this approach over the physical world is *aggregation*: instead of distributing intelligence into many independent units, the aggregation allows us to have a macro-view, and coordinate the action-perception process through a larger, 'higher' level system.

The result is the ability to reduce the complexity of the situation into computationally manageable chunks. The drawback is reduced individuality and less spontaneity: the perception-action process is more prescribed and more coordinated than would happen in the physical world. We consider this limitation acceptable, because the purpose of the simulation is to visualize the macro-characteristics of the building-in-use process.

To represent the process of use of a building in its evolving during time we also introduce the concept of the use scenario. A scenario describes a real-world example of how one or more people or organizations interact with a system (Hackos and Redish, 1998) – in this case a built environment – to reach objectives defined by their specific tasks and objectives. It provides a representation of building use by means of a logical path of occurrences and actions for a subsequent usability testing. In our approach, each of these steps, or milestones, is considered an event entity. Due to the complexity of a building use scenario, its representation is not a simple, single path of events, but a more complex directed graph, a combination of several logical paths that can interfere and affect each other (Figure 2).

In our system, events are representations of occurrences involving Actors, Spaces and Activities, but they are also a system of algorithms to be run during the

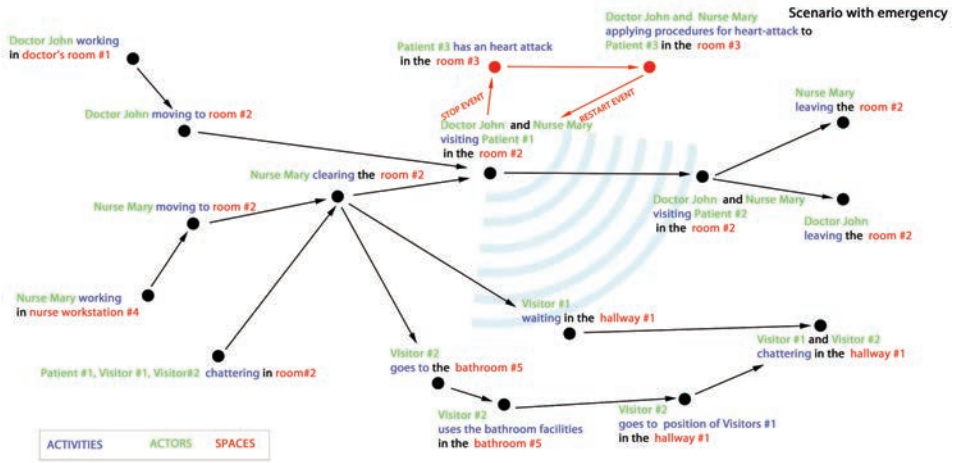

Figure 2. Scenario as network of events, and its adaptability to the status of the model.

simulation. Depending on the status of the model and on stochastic components, distinct events will be activated, leading to different outputs. Furthermore, in accordance to the outcome of every single event, a new list of events will be provided by the scenario sequence, allowing the system to choose different paths in the network. This *adaptation* process provides a representation of the usage of a building and highlights the way activities are developed and affected by the design of the built environment.

3. Simulation Conceptual Model

The starting point of any simulation experiment is a model of the system to be simulated. In a simulation model, considered as system generator, two main components are usually distinguishable: the first is oriented to a static representation, concerning existence of certain entities. The second involves a dynamic representation, concerning with changes (Haylor, 1969). In accordance with this assumption, our model consists of two parts, a knowledge base and a simulation environment (Figure 3).

By providing the simulation with a knowledge base, it is possible to represent all the data, concepts and relationships necessary to describe valid hypothesis for the simulation. Without a reliable and well-structured hypothesis system, the simulation would produce results that are far from real phenomena, even with an accurate simulation model. The knowledge base represents a set of entities involving both the building's form and function – such as spaces, building components, activities, furniture, equipments, etc. – and the users who will to populate it – such

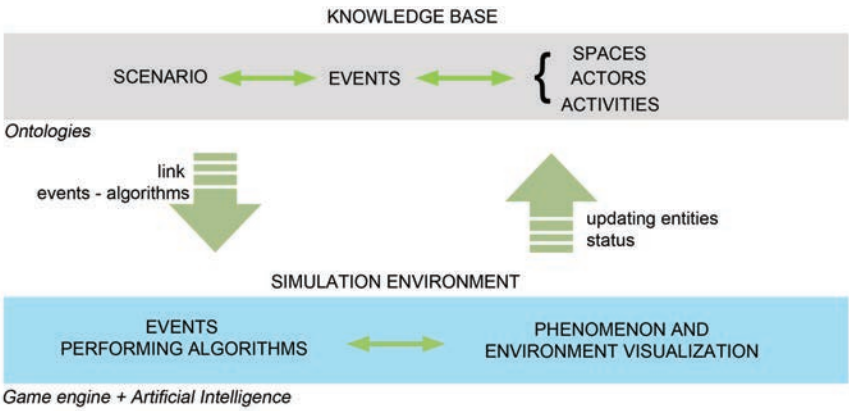

Figure 3. The two levels of the simulation model.

as workers, visitors, etc. Each of these entities is defined by a set of properties related to the specified object and by a list of relationships and interdependencies with other objects. But a mere representation of the world's objects is not sufficient to provide a reliable knowledge base for a simulation. What is needed is also a representation of changes and dynamic processes in which these objects are involved. To provide this representation, we chose to include *events* and *scenario entities* in the knowledge base, to provide data about the behavioural processes to be simulated. These process entities are represented in the same way of other object entities and are connected to them, so if we look at the entire knowledge base, we can see a network in which nodes are objects, activities, actors, events, scenarios and edges are the different relationships among them.

We build and manage this knowledge base by means of ontologies. The choice of an ontological model gives us the possibility to represent all the different heterogeneous entity classes (scenario – events – objects) in a homogeneous form, and to make explicit all the related semantic and the relations among them. In addition, the ontology-based system allows for the creation of specific instances with specific properties' values, defining discrete objects and connecting them to the simulation level. To build the knowledge base and represent this semantics, we have chosen to use the ontology modelling system *Protégé*, a Java-based open source ontology editor and knowledge-base framework.

While the knowledge base provides a static representation of objects, people, and relationships among them, a simulation environment is what is needed to actually compute, simulate and visualize the behavioural processes as phenomena. Looking at the latest advancements in the video game industry, we chose to use a game engine consisting of a 3D graphics simulator and a manager level for entities and behaviours: the first part defines the place where the entities (people, building and all the physical objects) are graphically represented in a 3D space where we can observe the objects' dynamics (people's behaviour, objects' movements and transformations, etc.) while the simulation is running. The second part is where entities' and behaviour data and scripts, necessary to actually run the simulation, are allocated. In this component of the game engine, each entity is associated with a system of properties slots and related values that will be changed and updated in real time during the simulation. To run the event simulation in the game engine, each activity has to be implemented using a series of algorithms (conventionally grouped in embedded scripts named "behavioural blocks"), methods that the engine will execute to generate and manage objects actions and behaviour in the 3D visualization space.

To represent and visualize the users and their activities in a 3D simulation environment we chose *Virtools*, a video game engine developed by Dassault Systèmes', integrated with compatible Artificial Intelligence libraries. Designed

for fast rendering, it can represent dynamic activities and embedded intelligence in the moving objects, which can be made context-dependent. In the game engine, we decided to distribute AI tasks at different levels in the simulation. At the Scenario level, the Artificial Intelligence provides control of the main narrative, activating step by step the events and choosing among different events by evaluating the state of the environment; it is very similar to a movie director's task, activating and governing the development of the events. To control the single event performing and development, we decided to use AI capabilities also within the event itself in order to reliably represent the single event phenomenon, directing the actors and the objects involved after the activation of the event by the scenario level AI and until has completed performing.

The connection of these two levels is what we consider as the use narrative. But this narrative is not sufficient to provide a reliable and adaptable simulation. As a matter of fact, this "story" will be too rigid and not applicable to different built environments testing. So, we chose to provide also actor/agent entities with some degree of autonomy, in order to give them the possibility to adapt some local behaviours (such as collision avoidance, or path computing). In the same way, also the process of computing the path and other low level actions and interactions with other objects will be controlled directly by the actors AI. In this way, we can get a compromise solution between a too rigid narrative and a too arbitrary agent-based system, in order to test the built environment in specific use conditions but also giving to the use scenario the possibility to adapt, within certain limits, to the status and the occurrences in the simulation.

4. Case Study: Testing an Hospital Ward

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 et al., 2010). At the same time, although hospitals are relatively complex buildings, as currently conceived and designed they are highly specialized "machines" whose purpose is to "fix" ailing patients. They use a relatively straight-forward, standardized use pattern, which is advantageous for this research since it provides a comprehensive, and agreed-upon, data set against which the model can be tested. Based on these assumptions, we chose to apply the model to the simulation of human behaviour and activities in a simple hospital ward. We have developed a double scenario in order to test typical activities within the ward and a special occurrence as an emergency in a random patient's room. In this study case, we have simulated how different spatial configurations affect the same use scenario, improving or hinder-

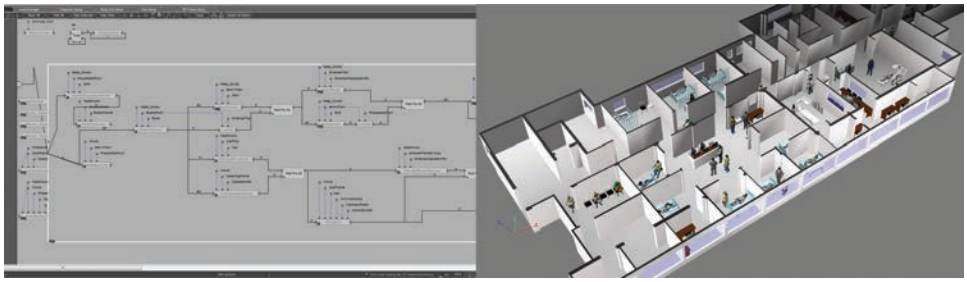

Figure 4. A part of the scenario scripting and its simulation in the virtual environment.

ing operational activities, patients control by nurses, accessibility in case of emergency, etc (Figure 4).

Currently, we are applying the same scenarios to an already built hospital, in order to compare the simulated functioning with the real world functioning, and validate the structure and the results of the modelling approach (To witness the dynamic behaviour of the model, see (Bnai Zion, 2013)).

5. Conclusions

We have described in this paper the development of a modelling approach aimed at simulating human behaviours and activities in a not-yet-built environment. The central idea of this approach is to build a clear representation of building use as narrative, a sequence of computational chunks called events, and to use it as hypothesis and "plot" of the simulation. Comparing our event-based approach to current "pure" agent-based systems, we believe that our model will offer a more manageable and coherent representation of cooperation and collaboration among different people during the building usage. The choice to build a predefine sequence of events and to apply it to the built environment model will provide a simulation based on strong hypothesis rather than a sum of single and autonomous behaviours (as in ABM), affording designers the possibility to actually evaluate how the built environment will affect a specific operational case.

A better comprehension of how people will use and interact with the built environment will necessary impact the design process. Therefore, we believe that the possibility to provide a reliable prediction of how people will behave in a building before its actual construction could allow the designers to evaluate the final quality of an architectural product and, in case of emergent usability problems, critical points, or inconsistencies, to intervene by improving its quality, its liveability, and reducing unnecessary costs.

References

"Bnai Zion": 2013, Available from: <http://www.youtube.com/watch?v=3OKgipQ6Pbs/> (accessed 1 April 2013).

Cenani, S. and Çagdas, G.: 2008, Agent-Based System for Modeling User Behaviour in Shopping Malls, *Proceedings of the 26th eCAADe Conference*, Antwerpen (Belgium) 17-20 September 2008, 635–642.

Cohen, U., Allison, D. and Witte, J.: 2010, *Critical Issues in Healthcare Environments*, Research Report for the Center for Heath Design, Concord CA.

Hackos, J. T. and Redish, J. C.: 1998, *User and task analysis for interface design*, John Wiley & Sons, Inc., New York, NY.

Haylor, T. H (ed.).: 1969, *The Design of Computer Simulation Experiments*, Duke University Press, Durham, N.C.

Heidegger, M.: 1962, *Being and Time*, Trans. by John MacQuarrie and Edward Robinson, Harper & Row, New York.

Kalay, Y. E.: 2004, *Architecture's New Media: Principles, Theories, and Methods of Computer-Aided Design*, MIT Press, Cambridge, MA.

Kalay, Y. E. and Irazabal C.: 1995, *Virtual Users (VUsers): Auto-Animated Human-forms for Representation and Evaluation of Behaviour in Designed Environments*, Technical report, Department of Architecture, UC Berkeley.

Kaplan, S. and Kaplan, R.: 1982, *Cognition and Environment: Functioning in an Uncertain World*, Prager, New York.

Kirwan, B. and Ainsworth, L. K. (eds.): 1992, *A guide to task analysis*, Taylor & Francis, Philadelphia, PA.

Koutamanis, A. and Mitossi, V.: 1996 Simulation for Analysis: Requirements from Architectural Design, *Proceedings of the 6th European Full-Scale Modeling Association Conference*, Vienna 1996, 96–101.

Krawczyk, M. and Novak, J.: 2006, *Game Development Essentials: Game Story & Character Development*, Delmar Cengage Learning, Clifton Park, NY.

Lawson, B.: 2006, *How designers think: the design process demystified*, Elsevier Architectural Press.

Magerko, B., Laird, E., Assanie, M., Kerfoot, A. and Stokes, D.: 2004, AI Characters and Directors for Interactive Computer Games, *Artificial Intelligence*, AAAI Press, 1001, 877–883.

O'Sullivan, D. and Haklay, M.: 2000, Agent-based models and individualism: is the world agent-based?, *Environment and Planning A*, 32(**8**), 1409–1425.

Ozel, F.: 1993, Computer Simulation of Behaviour in Spaces, *in* D. Stokols and R. W. Marans. (eds.), *Environmental Simulation – Research and Policy Issues*, New York, Plenum Press, 191–212.

Steinfeld, E.: 1992, Toward artificial users, *in* Y. E. Kalay (ed.), *Evaluating and predicting design performance*, John Wiley & Sons, New York, 329–346.

Yan, W. and Kalay, Y. E.: 2004, Simulating the Behaviour of Users in Built Environments, *Journal of Architectural and Planning Research (JAPR)* 21(**4**).

Wurzer, G.: 2009, Systems: Constraining Functions Through Processes (and Vice Versa), *Proceedings of the 27th eCAADe Conference*, Istanbul (Turkey), 16-19 September 2009, 367–373.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 209–218. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

ENERGY PERFORMANCE MODELING OF AN OFFICE BUILDING AND ITS EVALUATION

Post-occupancy evaluation and energy efficiency of the building

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Abstract. Energy performance modelling can provide insights into the efficiency and sustainability of commercial buildings, and also the achievement of certification standards such as USGBC LEED. However, the results from the modelling must be validated via a post-construction evaluation, which quantifies any discrepancies between the predicted energy usage and the actual energy consumed. In this study, an existing office building was examined to test how well the model predicts energy usage. The results from the model were compared with the actual usage of gas and electricity over two years (2010–2011). Our study showed a 123% higher gas usage, and a 36% lower electricity, compared with the simulation. This difference presents that occupant behaviour and building construction practices have significant impact on the energy usage of a building. For instance, the large discrepancy among gas usage is due to the office building's thermal envelope, which identifies the spots at which heat leaks out of the building, thereby forcing the heating unit to work more. Additionally, the post occupancy evaluation study identified that indoor environmental conditions impact on energy consumption of the building.

Keywords. Building performance evaluation; energy modelling; energy usage; user behaviour; post occupancy evaluation.

1. Introduction

1.1. ENERGY USE IN BUILIDNGS

Energy performance modeling provides an insight into understanding their efficiency and sustainability of the building. However, there is often a discrepancy between simulation and actual energy usage of buildings. The reasons for the differences are generally poorly understood and often have more to do with the role of human behavior than the building design.

Table 1. Main factors that influence building energy consumption (Yoshino, 2009).

Building-related factors	1) Climate
	2) Building envelops
	3) Building systems
User-related aspects	4) Operation and Maintains (O&M)
	5) Occupant's Behavior
	6) Indoor Environmental Quality (IEQ)

One of the major barriers for substantially improving energy efficiency in buildings is the lack of information about the factors determining the energy use of the building. In general, building energy consumption is mainly influenced by six factors shown in Table 1. One limitation of current research would be that it focuses mostly on building-related factors, such as climate, building envelope and HVAC systems rather than human related aspects (Yoshino, 2009). All of the factors, however, including building operation, occupants' activity and behavior, and indoor environmental quality, need to be analyzed using real measured energy consumption data (Effinger, 2012).

1.2. INDOOR ENVIRONMENTAL QUALITY AND ENERGY SAVINGS

Post occupancy evaluation (POE) is one of the most important efforts for energy consumption reduction while enhancing indoor environmental quality and occupant satisfaction. Raftery et al pointed out that user patterns would be a one of the important factors for total energy consumption modeling and adjustment of error (Raftery et al., 2009). Loftness et al pointed out that measured field data on IEQ, user satisfaction and the technical attributes of building systems (TABS) supports ongoing opportunities for energy conservation while meeting IEQ standards (Loftness et al., 2009). The Carnegie Mellon University (CMU) team has field findings for the General Services Administration (GSA) portfolio of offices that include 4% total energy savings by raising summer set points, 40% lighting energy savings by reducing ambient lighting and 25% reduction in lighting energy by daylight harvesting (Loftness et al., 2009; Aziz et al., 2012)

1.3. OBJECTIVES

The goal of this study is to better understand and strengthen the knowledge for effective total energy usage in buildings by analyzing energy usage and expenses, sustainable practices and materials during construction, and the indoor environment quality.

We highlight areas of efficient performance, as well as deficiencies within the building. Following our assessment, we provide strategies that can improve its energy efficiency, occupant comfort and the building's marketability through additional the U.S. Green Building Council (USGBC) Leadership in Energy and

Environmental Design (LEED) certification. These strategies will also factor in the cost of adopting the recommendations to provide the building owner with insights into the return from such investments, since not all benefits are quantifiable.

2. Methods

Our approach for assessing the overall performance of the TAI+LEE commercial building is to focus on three areas: thermal envelope, energy usage and indoor environment quality.

The energy usage comparison was conducted through the use of gas and electricity bills dating back to May 2010. This data was then compared to the energy simulation conducted using the eQUEST DOE-2 based simulation modelling tool. Energy consumption was normalized for the heating and cooling degree-days to determine how well the building was actually performing. The data from the energy bills were also inputted into the REM/Rate^{TM} software to provide a HERS rating, which also helped quantify our own recommended retrofit strategies.

To evaluate the thermal envelope, we used a thermo graphic camera to take pictures of the building exterior, work areas and the wall connections of the entire indoor space. This enabled us to identify areas of heat loss inside and outside the building. We also researched the materials of the building and their respective U-Values to compare with our actual findings from the pictures taken.

Lastly, indoor environmental quality field measurements were taken over two days in the TAI+LEE office building. The first measurements were taken on April 2nd, 2012, and the second set on April 17 and 18, 2012. Both were workdays with a number of employees present in the office.

On the first day, thermo graphic pictures, digital photos, surveys and NEAT cart measurements were taken for all rooms and spaces, including the basement.

The subsequent days were used to capture additional thermo graphic and digital pictures, conduct interviews, distribute longer occupant surveys, and setup the 24-hour Airquity measuring system.

3. Analysis of Current Condition

3.1. BUILDING INFORMATION

The building in this case study is TAI + LEE Architects in Pittsburgh, PA and is owner occupied (Figure 1). It has 1 ½ floor plus a basement. The total floor area is 1,650 ft^2 (153 m^2) with a conditioned volume of 23,100 ft^3 (654 m^2). The total wall and window area is 2,716 ft^2 (252 m^2) and 182 ft^2 (27 m^2), respectively. When the TAI+LEE group took over the building it had to be completely reconstructed since there was no insulation, and the roof had caved in. Therefore, they had to start from scratch by reconstructing the floor, walls and roof.

Figure 1. Floor plan, exterior, and interior photo.

3.2. BUILDING ATTRIBUTES AND CONTROLS

The radiant floor system serves as the primary heating unit for the building. It has a much smaller rated output of 42 kBTU/h versus 117 kBTU/h for the standard building. Its performance ratings are 96 for the EFF and 17 for the EER, compared to 80 and 8.9 for the traditional unit.

TAI+LEE also installed a supplemental air heat pump to heat and cool the building during extreme weather conditions. Although this system was installed to operate under the most extreme weather conditions, it is a high efficient system with a variable speed blower motor and is rarely used throughout the year.

The building is ventilated using two ERV systems, one in the basement (130cfm) and one on the first floor (200cfm) above the bathroom. The unit in the basement must be in constant operation to help control for humidity. However, the unit in the first floor is not used as often, since it is sufficient to manually ventilate the space by opening the windows on the north and south walls and the skylights.

Interviews conducted with the employees revealed that the indoor thermal controls were complicated to use, and most preferred to leave it alone. There are multiple devices for controlling various systems in the building. When the building was first finished, the central thermostat did not have an automated timer. This resulted in a significant time lag between when it was turned on and when the radiating floors would come into effect. A workaround for this was to turn on the heat pump while the radiating floor system took time to ramp up. Consequently, this resulted in higher electricity use until they installed an automated mechanism that set the temperature to 72°F (22.2°C) at 6 AM in the morning and 65°F (18.3°C) after 8 PM and on weekends.

The Mitsubishi controller is responsible for the ERV, AC and heater. Under normal conditions, passive techniques for ventilation are used, such as opening the skylights or front and rear windows. We noticed that the employees rarely used this control due to its multiple settings and the necessity to readjust once comfort level is reached. Although they prefer passive techniques, it has its own inconveniences, as occupants tend to stay focused on work until the thermal comfort levels were unbearable. When the ceiling fan was turned on, it made a significant positive impact for air circulation.

4. Energy Analysis and Results

4.1. COMPARISON OF SIMULATION AND ENERGY BILL

An energy simulation was conducted on TAI+LEE via eQUEST software and was compared against a reference case commercial building with the same floor area, volume and weather conditions (Pittsburgh, PA, USA). Table 2 shows the detailed

Table 2. Energy simulation comparison between baseline building and current building.

Description	Baseline Case	Current building
Weather file	PTTSBRGH.ET1	PTTSBRGH.ET1
Floor Area, ft²	1650.0	1650.0
Surface Area, ft²	6016.0	6016.0
Volume, ft³	23100.0	23100.0
Total Conduction UA, Btu/h-F	484.1	307.2
Average U-value, Btu/hr-ft²-F	0.080	0.051
Wall Construction	Code, R=9.7	triplebrick+foam, R=20.7
Roof Construction	R20polyiso, R=20.1	R30polyiso, R=29.5
Floor type, insulation	Crawl Space, Reff=24.0	Crawl Space, Reff=31.9
Window Construction	3026 wood code, U=0.35,etc	3070 wood kolbe, U=0.26,etc
Window Shading	None	None
Wall total gross area, ft²	2716	2716
Roof total gross area, ft²	1650	1650
Ground total gross area, ft²	1650	1650
Window total gross area, ft²	158	309
Windows (N/E/S/W:Roof)	9/0/12/0:0	11/0/8/5:3
Glazing name	codedouble, U=0.35	kolbe, U=0.26
Operating parameters:		
HVAC system	DX Cooling with Gas Furn	DX Cooling with Gas Furn
Rated Output (Ht/SC/TC),kBtu/h	117/48/64	42/28/37
Rated Air Flow/MOOA,cfm	1962/248	1873/120
Heating thermostat	72.0 °F, no setback	72.0 °F, setback to 67.0 °F
Cooling thermostat	76.0 °F, no setup	76.0 °F, setup to 81.0 °F
Heat/cool performance	eff=80,EER=8.9	eff=96,EER=17.0
Duct leaks total %	11/10	2/0
Peak Gains; IL,EL,HW,OT; W/ft²	1.00/0.33/0.26/1.52	0.75/0.10/0.26/1.25
Added mass	none	none
Daylighting	no	no
Infiltration, in²	ACH=1.0	ACH=0.3
Results:		
Energy cost	1.500$/Therm,0.100$/kWh	1.500$/Therm,0.100$/kWh
Simulation dates	01-Jan to 31-Dec	01-Jan to 31-Dec
Energy use, kBtu	306455	101184
Energy cost, $	$6153	$2558
Total Electric (**), kWh	27160	18405
Internal/External lights, kWh	5011/2226	3758/675
Heating/Cooling/Fan, kWh	0/3503/3135	0/1562/1485
Hot water/Other, kWh	0/13286	0/10926
Peak Electric, kW	11.8	5.7
Fuel, hw/heat/total, kBtu	6680/207098/213777	6680/31701/38380
Emissions, CO2/SO2/NOx, lbs	61750/238/139	29269/150/80

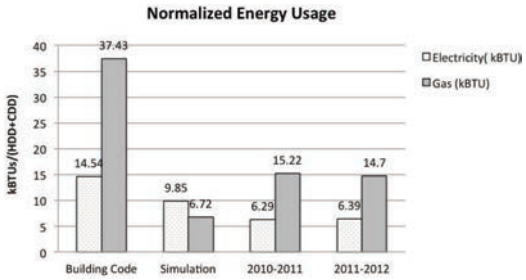


Figure 2. Normalized energy usage.

information of baseline data and current project. This building has a 36% lower average u-value for the entire building (0.051 btu/hr-ft2-f), with increased R-values coming from the roof, floor and windows construction. In addition, it employs a more efficient and smaller HVAC system due to the improved thermal envelope. In addition, it contained only 2% total duct leak, compared with the expected 11% for the reference commercial building. Therefore, TAI+LEE outperforms the reference case by 52% on cost and 32% on electricity use over the course of the year.

Although the simulation shows that the TAI+LEE building surpasses the reference commercial building, we wanted to compare the actual performance of the building to the simulated results. Based on the gas and electricity bills, TAI+LEE used a total of 130,807 and 103,171 kBTUs for the years 2010–2011 and 2011–2012, respectively. The simulation estimated a total energy usage of 101,184 kBTUs. However, the Heating degree day (HDD) and Cooling degree day (CDD) for 2008 may be different than those for which we analysed. Therefore, we normalized each year's total energy usage by its respective HDD and CDD and separated it by electricity and gas use (Figure 2).

Comparing their EUI to the 2003 CBECS data for office buildings, TAI+LEE fell within the 25th percentile for electricity use (6.98 kWh/sq. ft.). However, their natural gas (47.09 cf/sq. ft.) put them in the 50–75th percentile range. This agrees with the findings above that they are using electricity efficiently, but gas use is suboptimal – possibly due to leaks within the thermal envelope.

4.2. ESTIMATION OF ENERGY CONSUMPTION

We performed REM/Rate simulation to estimate the current energy cost. Also adding a green roof can increase the performance of roof envelopment. Adding a green roof under their Photovoltaics (PV) panels, as well as filling out the rest of their roof space with both components would increase the efficiency at which PV

panels perform, generate more electricity, and reduce the heating and cooling load of the building.

When we modelled the building in REMRate, the summation of all our recommendations amounted to an annual savings of $179, and improving our HERS index from 85 to 71. It is uncertain whether the REMRate model was able to capture benefits such as the reduction in heating and cooling load, but it also does not take into account the water runoff saved from employing a green roof. Because this renovation is capital intensive, TAI+LEE must perform a thorough investigation of its benefits before proceeding.

5. Building Envelope

5.1. THERMAL ENVELOP

The envelope of the building was constructed with high-quality, low U-Value materials. The Kolbe windows are double-paned argon filled gas, while the walls, roof and floor were constructed from low-waste wooden joists with Tripolymer foam insulation and minwool batt. Table 3 outlines the U-Value associated with each component of building.

One method to understand the large discrepancy among gas usage is to assess the office building's thermal envelope. This helps to identify the spots at which heat leaks out of the building, thereby forcing the heating unit to work more. A thermo-graphic camera identified multiple spots of heat loss on the front sidewall of the building.

In 2008, a blower door test was performed for this building. The simulated infiltration was 0.3 ACH (Air exchange per hour), but the results from the test returned 0.4 ACH. The leaks, which were from the wire installations of the solar PV panels located on the second floor, were supposedly fixed shortly thereafter. However, Thermal graphic image shows some residual heat loss at the junction between the roof joist and the wall. Also, there are additional leaks in the conference room as seen in Figure 3. Overall, the majority of the leaks occur in the north wall/area of the building.

Table 3. U-Value of thermal envelope.

Components	**U-Value**
Windows: Double-pane argon filled gas	0.260
Roof: Wooden joists with Tripolymer foam insulation	0.028
Walls: Wooden joists with Tripolymer foam insulation	0.05
Basement Concrete Wall	0.630
Floor: MinWool Batt	0.072

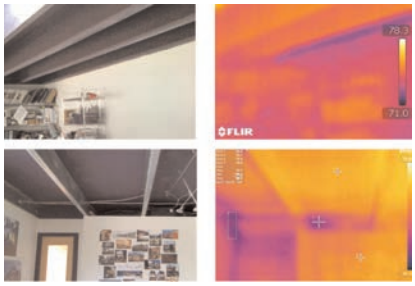


Figure 3. Thermal image of conference room.

5.2. IEQ EVALUATION: THERMAL QUALITY

In order to enhance the environmental profile of the work group beyond the descriptions possible with spot measurements, twenty-four hour continuous measurements were taken in one location of the office. An Aircuity Optima system is utilized to measure temperature, relative humidity, CO_2, CO, large and small particulates, TVOC, radon, and ozone. In this study, we are focused on thermal environmental qualities and findings. Table 4 shows the indices and user comfort standards for IEQ field measurement (ASHRAE, 2010).

Spot and 24 hour continuous air temperature measurements (1.1m, 0.6m, 0.1m) ranged between 68–78°F (20–25.6°C), average 73°F (22.8°C), comfortably within the seasonal comfort zone (Figure 4, Figure 5). Although all measurements fell

Table 4. The measurements taken at each workstation, as well as calculated variables.

Measures taken and units	**Standards**
Temperature at 1.1m, 0.6m, 0.1m (spot and 24 hour continuous)	ASHRAE 55-2010
Horizontal radiant temperature difference ^{o}C	ASHRAE 55-2010
Vertical radiant temperature difference ^{o}C	ASHRAE 55-2010
Relative humidity % (spot and 24 hour continuous)	ASHRAE 62-2010

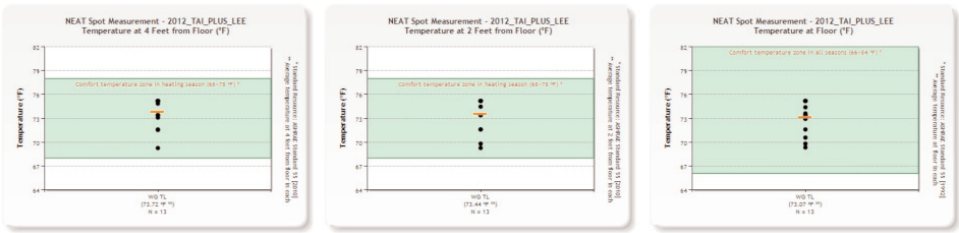
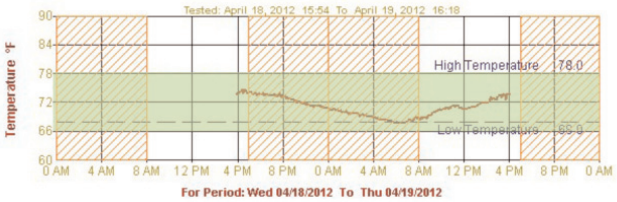


Figure 4. Spot measurement: air temperature at 1.1m, 0.6m and 0.1m from floor.



Aircuity 24hour measurement result:

	Temperature (°F)
Average Values	72
Extreme Values	68-75
Typical/Comfort	71 - 74
Recommended	68 - 78

Figure 5. 24-hour continuous measurement result: Air temperature.

within the comfort zone, we noticed the loft area was quite warmer than the first floor. The space is currently used only as a storage area.

6. Summary and Conclusion

The TAI+LEE commercial building was a well-thought out and executed retrofit on a dilapidated storage garage. Its use of high-quality, sustainable materials and selection of HVAC components are impressive. The electricity EUI was excellent as it fell within the 25th percentile of office buildings surveyed in the 2003 CBECS, and outperformed its energy simulation in 2008. In regards to the indoor environment quality, all measurements were within the comfort range and all employees enjoyed working in the building.

With that said, there were some areas that could have been improved. The natural gas EUI did not perform as well, since it fell within the 50-75th percentile of the 2003 (CBECS, 2003).

Comparative analyses showed that energy usage discrepancies between the predicted and actual usages were significant. Based on the gas and electricity bills, the building used a total of 130,807 and 103,171 kBTU for the years 2010-2011 and 2011–2012, respectively, whereas the simulation predicted a total energy usage of 101,184 kBTU.

Since the HDD and CDD may vary year by year, each year's total energy usage was normalized by its respective HDD and CDD and separated it by electricity and gas use. Although the simulation predicted the total energy use relatively well, larger discrepancies were found after differentiating between electricity (36% lower than actual) and gas use (123% higher than actual). In general a building simulation analysis is expected to predict the usage in less than 10% of error (Gundala, 2003). One method to understand the large discrepancy among gas usage is to assess the office building's thermal envelope. This helps to identify the spots at which heat leaks out of the building, thereby forcing the heating unit to work more. A thermo-graphic camera identified multiple spots of heat loss on the front sidewall of the building.

It infers that that occupant behavior and building construction practices may have significant impacts on the energy usage of a building. Accordingly, the design of a building needs to be incorporated with occupants' behaviors and interaction with their indoor environment. Additionally, it would be better that building codes and certification standards, such as USGBC LEED, include requirements for best practice at construction sites to ensure proper installation and storage of materials.

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References

ASHRAE: 2010, *Performance Measurement Protocols for Commercial Buildings*, American Society of Heating, Refrigerating and Air Conditioning Engineers.

Aziz, A., Park, J., et al.: 2012, Field measurement Protocols for Evaluating Indoor Environmental Quality and User Satisfaction in Relation to Energy Efficiency. U.S. DOE The Energy Efficient Buildings Hub, Department of Energy.

CBECS: 2003, 2003 Commercial Buildings Energy Consumption Survey (CBECS). Department of Energy, USA.

Gundala, S.: 2003, LEED Energy Performance Modeling and Evaluation of the S.T. Dana Building Renovations, Report No. CSS03-07, Center for Sustainable Systems, University of Michigan, Ann Arbor, MI.

Effinger, J., Effinger, M. and Kramer, H.: 2012, Overcoming Barriers to Whole Building M&V in Commercial Buildings, *2012 ACEEE Summer Study on Energy Efficiency in Buildings*, American Council for an Energy-Efficient Economy, Washington, DC.

Loftness, V., Aziz, A., Choi, J. H., Kampschroer, K., Powell, K., Atkinson, M. and Heerwagen J.: 2009, The value of post-occupancy evaluation for building occupants and facility managers, *Intelligent Buildings International*, **1**(4), 249–268.

Raftery, P., Keane M. and Costa, A.: 2009, Calibration of a detailed simulation model to energy monitoring system data: a methodology and case study, *Proceedings of the 11th IBPSA Conference*, Glasgow, UK.

Yoshino, H.: 2009, Total energy use in buildings: analysis and evaluation methods, ECBCS Project Factsheet, Annex 53, ECBCS, UK.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 219–228. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

PEDESTRIAN THERMAL COMFORT IN RELATION TO STREET ZONES WITH DIFFERENT ORIENTATIONS

A pilot-study of Rotterdam

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Abstract. This paper presents the impacts of different street orientations and street zones of a typical Dutch residential area on micro-scale human thermal comfort. The spatial and temporal variation of mean radiant temperature (T_{mrt}) of a typical summer day in Rotterdam, The Netherlands, is simulated by using an established long- and short-wave 3D radiation fluxes model (*SOLWEIG*). This model calculates human radiation load and expresses this as a T_{mrt}. Hereby we simulate and analyse the T_{mrt} variations for three zones of a street consisting of a centre area for cars and the adjacent pedestrian zones for pedestrians and bicycles. The streets are azimuth rotated. The simulation and analysis results show various T_{mrt} patterns of the three zones in the different orientations at different periods during daytime. We show that the spatial distribution of T_{mrt} at street level strongly depends on street orientation and street zone. This is crucial since optimizing street configuration will directly influence the human thermal comfort in relation to street orientation and street zone. Finally we present a time adjusted framework of thermal comfort and classify the various T_{mrt} for each zone and orientation.

Keywords. Thermal comfort; street orientation; street zone; mean radiant temperature (T_{mrt}); *SOLWEIG*.

1. Introduction

An increase of extreme summer heat waves around the globe is arising, which has a strong impact on thermal comfort of people (AR4 IPCC, 2007; National Assessment Synthesis Team, 2000). Urban design affects microclimates as well as the energy consumption of buildings. Thus the orientation of streets and their zones in their relationship to the sun is a key issue not only in design but also in

biometeorology. Outdoor and micro climate become increasingly popular issues and generates new collaboration between different fields of research (Brager and de Dear, 1998). However urban design knowledge on outdoor thermal comfort for pedestrians remains limited.

The mean radiant temperature (T_{mrt}) is an important thermo-physiologically relevant assessment index. Several European studies show that the perceived temperature during hot summer days directly relates to T_{mrt} (Mayer et al., 2008). T_{mrt} represents the human radiation exposure to all short and long wave radiation fluxes by weighting the directional components in all six directions (front, back, left, right, top and bottom) to represent the radiation load on a standardized human being (Matzarakis et al., 2007). Thorsson et al. (2011) have showed that the *Solar Long Wave Environmental Irradiance Geometry Model* (*SOLWEIG*) presents reasonable T_{mrt} simulation results for the urban canyon micro climate in Goteborg, which has a similar maritime climate as the Netherlands (Kottek et al., 2006). We selected for our simulation a typical summer day such as August 6th, 2009 (Figure 2) akin to Heusinkveld et al. (2010) urban heat stress assessment in Rotterdam via a mobile platform. Dai et al. (2012) shows that the SOLWEIG model compares well with Heusinkveld et al. (2010)'s survey results. We constructed a street model with variable building width and variable orientation and selected the same meteorological data set for our simulation and used SOLWEIG (Figure 3) as a model to simulate T_{mrt} in various urban settings, in order to get an overview of spatio-temporal distribution of T_{mrt} within different zones of a street with different orientations (Figure 4).

Some studies have showed that there is a relationship between urban form and human thermal comfort. For instance, Herrmann and Matzarakis (2012) conducted an analysis on T_{mrt} in idealised urban canyons using another radiation fluxes model called *RayMan* (Matzarakis et al., 2007), which is a point simulation model for modelling radiation in a complex 3D environment. They also considered the street orientation impact on T_{mrt} in idealised urban canyons; however they simulated the T_{mrt} along the centre line of the street only. Typically however, people are staying in pedestrian-zones which are usually located at the street side. Hence the mean or centre point's simulation result can't differentiate between different zones of street's T_{mrt} in detail. In our research we simulate T_{mrt} for three zones, namely the centre and two adjacent pedestrian zones to the left and right side of a street. While Thorsson et al. (2009) showed the spatial variations of T_{mrt} with four types of urban forms using SOLWEIG, our research focuses on the various street orientations and the impact of T_{mrt} on three zones of a typical street. Dai et al. (2012) also considered impact of street orientations, but they just considered North-South and East-West orientations. Bourbia and Awbi (2004) analysed six street orientations but limited their analysis to shading patterns instead of a T_{mrt}

spatial distribution which is more closely related to the human thermal energy balance or comfort. Ali-Toudert and Mayer (2007) considered E-W, N-S, NE-SW and NW-SE street orientations by a 3D non-hydrostatic model, called *ENVI-met* (Bruse and Fleer, 1998) in a subtropical location. However, in our study we focus on the spatial-temporal distributions of the three zones of a street in relation to their orientations in a temperate climate zone.

The main objective of this study is to investigate the relationship between street orientations and thermal comfort (characterised by T_{mrt}) of different zones of a street using the SOLWEIG model developed by the Göteborg Urban Climate Group (Lindberg and Grimmond, 2010; Lindberg et al., 2008; Lindberg and Thorsson, 2009). Hereby we simulate T_{mrt} for a typical Dutch residential suburb area with fixed height/width-ratio (h/w) of 1:1 in six azimuth orientations in 30° steps using the SOLWEIG model.

2. Method

A typical height (h) of 15m is selected for idealised urban buildings in Rotterdam and 15m is chosen for street' width (w) (akin to Herrmann and Matzarakis' model (2012) (h/w=1:1). Rotterdam (approximate Longitude 4°28' and Latitude 51°55') is a harbour city characterized by a temperate maritime climate influenced by the North Sea and Atlantic Ocean. We build a computer model of an artificial street by constructing a *Digital Elevation Model* (DEM). A DEM is a digital 3D model to present a terrain's surface (Holmes et al., 2000). Next, six urban canyon versions were constructed by rotating the DEM in 30° steps, namely 0°, 30°, 60°, 90°, 120° and 150° (Figure 1), hereby the situation in 0° is the same as that in 180°, and 30° is the same as 210° etc. In the third step, we simulate the streets in their different orientations in SOLWEIG using nearby weather station data and generate their T_{mrt} values for the two pedestrians and the centre zones (Figure 1). 3m is set as the width of pavements and 9m for the centre zone of the street. Finally we classify the simulation results into three T_{mrt} categories and relate them to the duration of exposure. Left and right is defined based on the orientation of the street starting from 0° and rotating to 150° as shown in Figure 1.

3. Simulation of T_{mrt} for different scenarios

The profile of August 6th, 2009 (Figure 2) matches best a diurnal distribution of temperature and global radiation (smoother diurnal distribution suggests less wind) which we select for our simulation from each profile of global radiation and temperature (temperature was almost 24 °C) of each day in summer 2009.

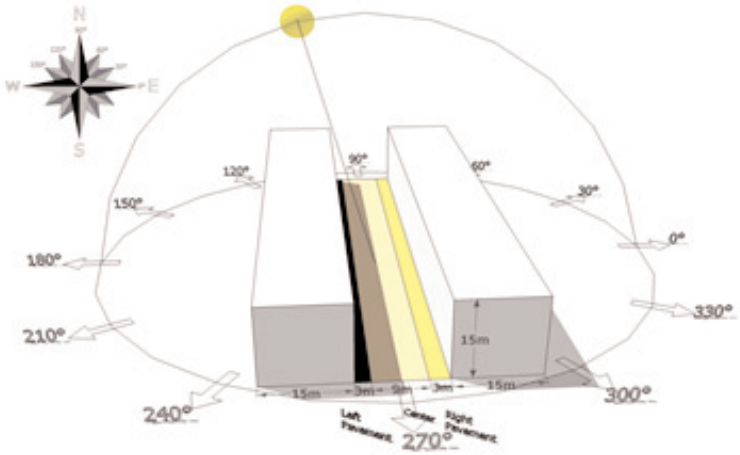

Figure 1. The idealized urban street scenario (h/w =1:1): showing the study areas of left and right pavements (each 3m) and the centre zone (9m) of a street and the six orientations.

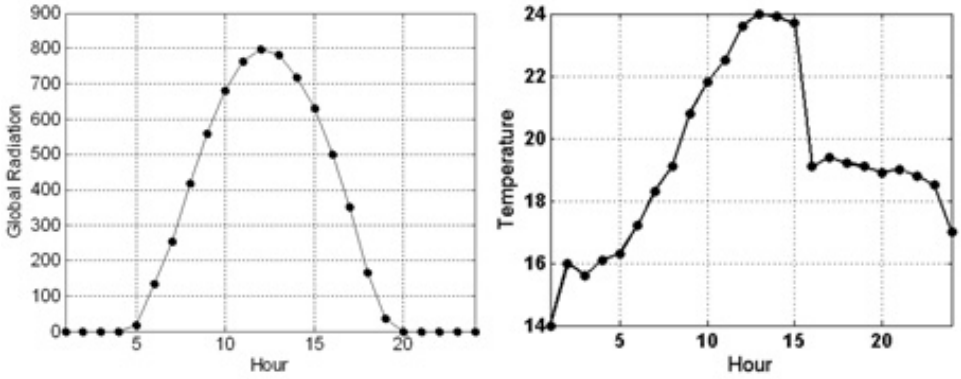

Figure 2. Profile of Global Radiation (left) in W/m^2 and Temperature (right) in °C of Rotterdam on 6th August, 2009.

Figure 3 shows the workflow for the SOLWEIG model. The Digital Elevation Model (DEM) (Step 1) is a digital 3D model to present a terrain's surface information (Holmes et al., 2000) to get the matching appropriate Sky View Factor (SVF) (Step 2). DEM first calculates SVF and it is the fraction of the sky visible from an observer' point of view within the street canyon. Then SOLWEIG uses the SVF to calculate solar radiation (direct and diffuse) for a given longitude, latitude, date and time. We use the default model parameters (Step 3), which

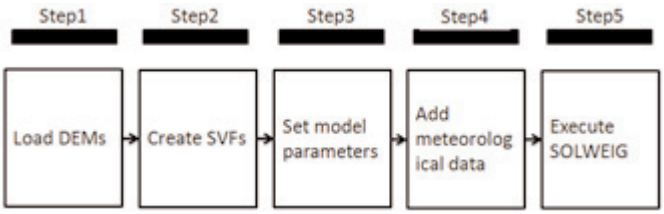

Figure 3. The five steps to simulate T_{mrt} *using the SOLWEIG model.*

appeared to simulate correctly for T_{mrt} within 60°C (Dai et al., 2012). Albedo (0.15), emissivity for surface (0.95) and emissivity for buildings (0.90) are given for this study, which are the same setting as Thorsson et al. (2011).

Then we synchronize August 6th, 2009, Rotterdam's meteorological data (Rotterdam WMO weather station Zestienhoven, source: KNMI, The Netherlands, 2012), which includes temperature, relative humidity and global radiation for the simulation day (Step 4) and finally we execute the software to simulate the T_{mrt} variation (Step 5).

4. Simulation Results

Figure 4 below shows the T_{mrt} simulation results in their six orientations. The simulation results allow us to study the impact of T_{mrt} in each street orientation for the three zones of the street. We focus on the daytime from 5:00 to 19:00.

Figure 4 also shows the diurnal profiles of T_{mrt} distributions in six street orientations during daytime (5:00-19:00, Coordinated Universal Time: UTC). The graphs show that the range of T_{mrt} of all orientations is between 16°C and 56°C.

We can see clearly the T_{mrt} differences in the 0° and 150° orientations and similar T_{mrt} patterns in 90° and 120° orientations. In the 0° orientation, the T_{mrt} of the left pavement is the highest reaching 56°C at around 11:00h, while the T_{mrt} of the centre zone is highest with 45°C at around 8:00h and the right pavement 43° at around 7:00h respectively. In the 150° orientation, T_{mrt} of the right pavement is the highest of 51° at around 12:00h, while T_{mrt} of the centre zone is the highest of 44°C at around 14:00 and the left pavement 34°C at around 15:00h.

In the 90° orientation, the three profiles are close to a Standard Normal Distribution (SND). T_{mrt} of the right pavement is highest (56°C) at 11:00h, while T_{mrt} of the centre is highest (50°C) at 12:00h and T_{mrt} of the left pavement is highest (48°C) at 13:00h respectively.

In the 120° orientation, the T_{mrt} of the right pavement is close to a SND and reaches the highest value (52°C) at 11:00h, while the T_{mrt} of the centre zone is

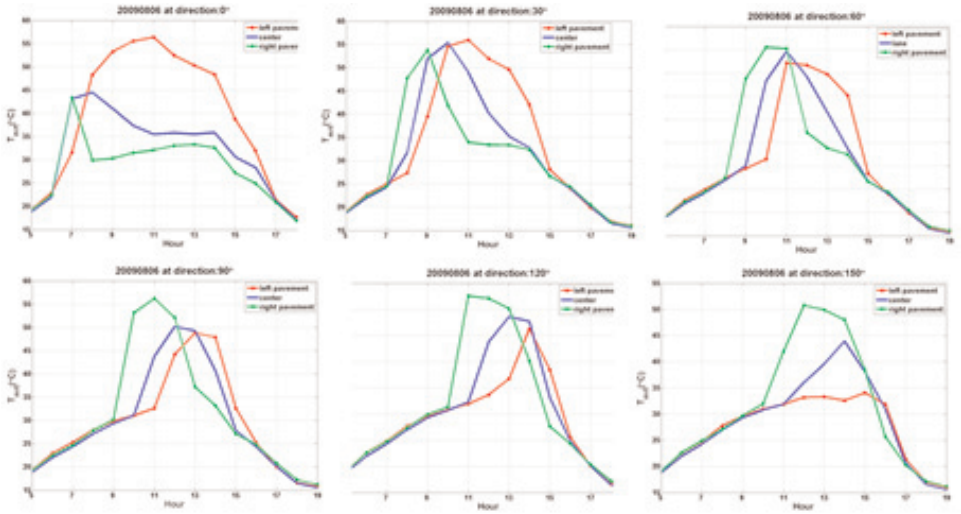

Figure 4. The profile of T_{mrt} *with six street orientations from 5:00 to 19:00 for left, right pavement and centre of street on August 6th, 2009 in Rotterdam.*

highest (48°C) at 13:00h and the T_{mrt} of the left pavement is highest (46°C) at 14:00.

Finally in 30° and 60° orientations, the highest T_{mrt} of the three zones are all well above 50°C from 9:00h to 13:00h during the simulation day.

In general, the right pavement is the first area to become warmer, centre is the second area to get the sunshine and the left pavement is the last zone. For the left pavement the T_{mrt} values are higher than that of the other zones in 0° and 30° street orientations. At the same time, T_{mrt} value of the left pavement becomes smaller for the other orientations. Due to the path of the sun and its subsequent exposure, the right pavement' T_{mrt} is higher in the 90°, 120° and 150° orientations. These would be used to translate to moderate heat stress as we can build buildings in a better orientation on a better part of street.

Mean, Standard Deviation, Maximum and Minimum of T_{mrt} are shown in Table 1. Based on our results, we use the statistical distribution (Mean plus or minus Standard Deviation) as a method to classify the thermal comfort into three levels: Normal (Level I), Warm (Level II) and Hot (Level III). The T_{mrt} of Level I are all below 20°C, Level II ranges between 20°C and 49°C and Level III has T_{mrt} values above 49°C. The three classifications are shown in Table 2.

Generally the T_{mrt} of Level I is considered as a comfortable normal temperature (note that T_{mrt} is different from air-temperature: it sums all short and long wave radiation fluxes and weights the directional components for each up or

Table 1. Mean, Standard Deviation, Max and Min of T_{mrt}

	***Tmrt* (°C)**
Mean	*34.2*
Standard Deviation	*14.2*
Max	*61.0*
Min	*15.3*

Table 2. The classification of Tmrt: three levels of thermal comfort: Level I: Normal, Level II: Warm, Level III: Hot.

Classification of thermal comfort	***Tmrt***
Level I: Normal	T_{mrt} <= 20°C
Level II: Warm	20° < T_{mrt} <= 49°C
Level III: Hot	T_{mrt} > 49°C

down), Level II is considered as warm – not hot, yet a longer time of exposure will make people feel uncomfortably warm; and Level III is considered as hot to extreme hot. Matzarakis et al. (1999) links Physiologically Equivalent Temperature (PET) to human thermal comfort. They consider "PET > 35" as "Hot, strong heat stress", and "PET around 23" as "Comfortable, no thermal stress". Mayer et al. (2008) find the relationship between T_{mrt} and PET according to their European study results using linear regression. Our classification method aligns with the results of both Matzarakis et al. and Mayer et al.

The left side of Figure 5 presents the detailed spatio-temporal distribution differences of T_{mrt} in the three zones of the street. Using the above three level classification we can re-represent our findings clearer as shown on the right scale of figure. In general, when the left pavement is hot (level III), the right one is cool (Level I), and vice versa. The hottest T_{mrt} of the day is around noon. In the 0° orientation, the left pavement sustain high T_{mrt} of above 49°C. The T_{mrt} remains in this level for ca. 6 hours, which means that it is highly uncomfortable and we subsequently reclassify it in a time-adjusted Level III.

Table 3 shows the time-adjusted classification of three zones and their orientations. From Figure 5 (right), we can see that some parts of T_{mrt} in Left 30°-, Centre 30°-, Right 90°- and Right 120°-zones are below 49°C, which is within the range of Level II. Since the T_{mrt} in these orientations remain above 49° for a longer period of time (about 3 hours), we subsequently reclassify them into category Level III. While some parts of T_{mrt} in Left 90°-, Centre 60°-, Centre 90°-, Right

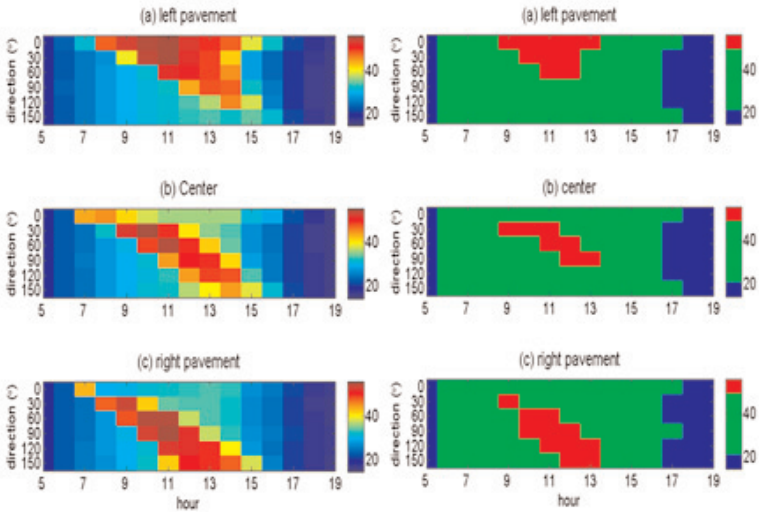

Figure 5. Left: Average of three zones' Tmrt (°C) with the 6 street orientations from 5:00 to 19:00. Right: Our three level classification results for three zones' Tmrt (°C).

Table 3. The time-adjusted classification of three zones and their orientations: Level I: Normal, Level II: Warm, Level III: Hot. Bold indicates the new classification.

Level III		**Level II**		**Level I**
Around 6 h	**Around 3 h**	**Around 2h**	**Around 1h**	**Around 0h**
Left 0°	**Left 30°**	**Left 90°**	Right 30°	Left 60°
	Centre 30°	**Centre 60°**		Left 120°
	Right 90°	**Centre 90°**		Left 150°
	Right 120°	**Right 60°**		Centre 0°
		Right 150°		Centre 120°
				Centre 150°
				Right 0°

60°- and Right 150°-zones are in Level III, but only for a short period of time (less than 2 hour), we assign them to Level II.

5. Conclusion and Limitation

The simulations performed in this study show that street orientation and the three different zones of a street (right-, left pavement, and centre zone) play an impor-

tant role on the local T_{mrt}. We have simulated separately the three zone of a street and various orientations to distinguish T_{mrt} during typical summer day. The results show that the thermal comfort of the three zones varies: there are large T_{mrt} differences between 0° and 150° orientation, and 0° is hotter than 150°. For example, shading elements or trees can reduce the heat gain of the left pavement in the 0° orientation, the right pavement in the 90° orientation and three sides in 30° and 60° orientations; or in Rotterdam's context street orientations of 120° and 150° are better than the others orientations. As the thermal comfort for two pavements plays an important role to people's lives, the simulation results can aid in the urban design and planning in respect of micro-scale climate issues.

Further research has to be done to include elements such as monthly heat stress (different months have various sun angle) and other factors, such as vegetation, building materials, building types, shading, building/street forms, wind, anthropogenic heat, etc. In addition there are subjective factors impacting the thermal comfort of people, like personal feelings or people's activities. Next we plan to transfer this study to a variety of other climate zones to test its universal validity. Finally our research aims to combine all the said elements into a parametric model to establish and analyse spatio-temporal dependencies of urban form to thermal comfort.

References

Ali-Toudert, F. and Mayer, H.: 2007, Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate, *Building and Environment*, **42**(3), 1553–1554.

"AR4, IPCC": 2007, Available from: Open Source Repository <http://www.ipcc.ch/publications_and_data/ar4/syr/en/main.html> (accessed 1Dec 2012).

Bourbia, F. and Awbi, H. B.: 2004, Building cluster and shading in urban canyon for hot dry climate Part 2: Shading simulations, Renewable Energy, **29**(2), 291–301.

Brager, G. S. and de Dear, R. J.: 1998, Thermal adaptation in the built environment: a literature review, *Energy and Buildings*, **27**(1), 83–96.

Bruse, M. and Fleer, H.: 1998, Simulating surface-plant-air interactions inside urban environments with a three dimensional numerical model, Environmental *Modelling and* Software, **13**(3–4), 373–384.

Dai, Q., Schnabel, M. A., Heusinkveld, B.: 2012, Influence of height-to-width ratio: Case study on mean radiant temperature for Netherlands buildings, *The 46th Annual Conference of the Architectural Science Association (ASA2012)*, Goldcoast, Australia. 8 pages.

Herrmann, J. and Matzarakis, A.: 2012, Mean radiant temperature in idealised urban canyons-examples from Freiburg, Germany, *International Journal of Biometeorology*, **56**(1), 199–203.

Heusinkveld, B. G., Hove, L. W. A. van, Jacobs, C. M. J., Steeneveld, G. J., Elbers, J. A., Moors, E. J., Holtslag, A. A. M.: 2010, Use of a mobile platform for assessing urban heat stress in Rotterdam, *Proceedings of the 7th Conference on Biometeorology*, Freiburg, Germany, 433–438.

Holmes, K. W., Chadwick, O. A. and Kyriakidis, P. C.: 2000, Error in a USGS 30-meter digital elevation model and its impact on terrain modeling, *Journal of Hydrology*, **233**(1–4), 154–173.

Lindberg, F. and Grimmond, C. S. B.: 2010, Continuous sky view factor maps from high res-olution urban digital elevation models, *Climate Research*, **42**(3), 177–183.

Lindberg, F., Holmer, B. and Thorsson, S.: 2008, *SOLWEIG* 1.0 – Modelling spatial varia-tions of 3D radiant fluxes and mean radiant temperature in complex urban settings, *Inter-national Journal of Biometeorology*, **52**(7), 697–713.

Lindberg, F. and Thorsson, S.: 2009, *SOLWEIG* – the new model for calculating the mean radiant temperature, *The seventh International Conference on Urban Climate*, Yokohama, Japan. 17 pages.

Matzarakis, A., Mayer, H. and Iziomon, M. G.: 1999, Applications of a universal thermal index: physiological equivalent temperature, *International Journal of Biometeorology*, **43**(2), 76–84.

Matzarakis, A., Rutz, F. and Mayer, H.: 2007, Modelling radiation fluxes in simple and complex environments – application of the RayMan model, *International Journal of Biometeorology*, **51**(4), 323–334.

Mayer, H., Holst, J., Dostal, P., Imbery, F. and Schindler, D.: 2008, Human thermal comfort in summer within an urban street canyon in Central Europe, *Meteorologische Zeitschrift*, **17**(3), 241–250.

Kottek, M., Grieser, J., Beck, C., Rudolf, B. and Rubel, F.: 2006, World Map of the Köppen-Geiger climate classification updated, *Meteorologische Zeitschrift*, ***15***, 259–263.

"National Assessment Synthesis Team, US Global Change Research Program": 2000. Available from: Open Source Repository <http://www.vaccinationnews.com/DailyNews/June2002/ClimateChangeImpacts21.htm > (accessed 1 December 2012).

"Rotterdam WMO weather station Zestienhoven, source: KNMI, The Netherlands": 2012. Available from: Open Source Repository <http://www.knmi.nl/klimatologie/uurgegevens/#no.> (accessed 20 September 2012).

Thorsson, S., Lindberg, F., Bjorklund, J., Holmer, B. and Rayner, D.: 2011, Potential changes in outdoor thermal comfort conditions in Gothenburg, Sweden due to climate change: the influence of urban geometry, International Journal *of Climatology*, **31**(2), 324–335.

COLLABORATIVE AND PARTICIPATORY DESIGN

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OPEN COMMUNITITION

Competitive design in a collaborative virtual environment

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Abstract. The recent enthusiasm in popular culture for massively multi-player online environments has proven that eclectic online communities have the potential to develop powerful problem solving capacities, through the enactment of a collective intelligence. Foreseeing a radical change in the identity of the architect, becoming but the designer of open systems of emergent communal design environments, this paper aims at making the case for an alternate CAAD model. Rather than a fully collaborative approach, the open system proposed here encourages direct competition within a shared online environment, based on an established precedent in an associated design field known as 'communitition'. After establishing this alternate position for collaborative CAAD, outcomes from a pilot study are discussed and the specification of a full case study is presented.

Keywords. Collaborative design; virtual environments; competition.

1. Introduction

1.1. COLLABORATIVE VIRTUAL ENVIRONMENTS

Within the last ten years, the CAAD scene has shown a growing interest in the potential of Collaborative Virtual Environments (CVE). Following the technological advancements, CVEs utilize a wide range of interactive hardware, from multi-touch tabletop (Chen and Schnabel, 2011), to Virtual Reality (VR) Caves (Frost and Warren, 2000). Software wise, CVEs have drawn from traditional 2D and 3D representational CAAD tools, videogame engines (Moloney and Harvey, 2004), or a mix of both (Frost, 2003). Our field of interest, being that of multi-user collaborative virtual worlds, has been proven by Merrick et al. (2010) to be useful for collaboration as "(1) design tools for modeling new artefacts, (2) support for communication, and (3) the ability to incorporate artificial models of

cognitive design processes". These CVEs, have reflected on these conceptual fields, looking at either finding new educational paradigms (Merrick et al., 2010), or generating models of existing states of practice (Karakaya and Senyapılı, 2006). However, Achten and Beetz (2009) note in their literature review on the development of design collaboration that "Much of the work in the field is technology driven." and that "[…] we probably lack publications from the managerial and psychological perspective." Moreover, a closer look at the previous works reveals two recurrent issues that hinder the success of CVEs. Firstly, many experiments denote the difficulty of implementing satisfactory motivational mechanisms. Secondly, we can witness that users tend to struggle with learning a new design tool.

Most precedents in CVE show small-scale groups of specialists in action. Yet Achten et al. (2011) remark that there is a new trend of involving bigger crowds in the problem solving process. The concept of collective intelligence, as defined by Pierre Lévy (1997), has been explored as a means to exploit the innovative capacity of a group of non-specialists, notably through crowd sourcing (Brabham, 2008). More recently, Collective Intelligence has been related back to the architectural design process by Paulini et al. (2007), who agree on the potential, but note the inconsistency of the crowd sourcing model to organize and perform better than a smaller team of specialists.

1.2. OBJECTIVE AND AMBITIONS OF THE RESEARCH

An alternate model to the consensus model of collective intelligence applied to collaborative design, is that of explicit competition within a shared environment. As an example, the lighting company Osram leveraged the collective intelligence of online communities through a monetary incentive. Social network analysis of the Osram competition reveal there is a correlation between highly competitive behavior (with a degree of collaboration) and innovative design. Hutter et al. (2011) capture this mode of competitive, but communal design activity through the term 'communitition'. The principle is that "while competition reduces collaboration, it also spurs community members' interest in innovation activities." There is an analogy with the tradition of architectural design competitions, which have continually driven innovation in architecture. Typically in architecture however, participants have no knowledge of other contestant's designs until the competition has been judged. The precedent of the Osram competition reveals that been able to track other design development and *communicate while competing* was an essential factor in successful innovation.

"… that ideas submitted by communititors – users combining co-operative as well as competitive features – show a higher probability of being highly ranked by

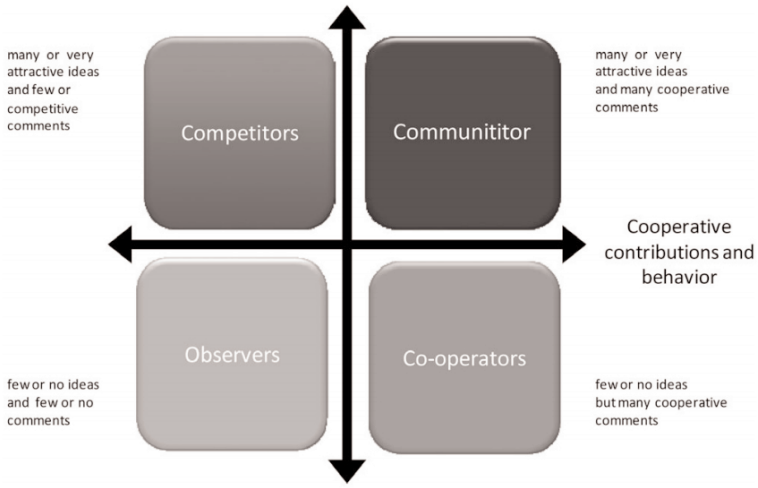

Figure 1. Different User Types Identified in the Osram study (Hutter et al., 2011).

community evaluation and winning. These findings indicate that engaging in competitive behavior aimed at winning the contest while simultaneously participating in community collaboration may positively correlate with the quality of the submitted designs." (Hutter et al., 2011)

The following pilot study explores how such a model may be evaluated for architectural design. The ambition underpinning this is the premise that the architectural design will gravitate to a more open system that operates at a 'meta-level', above the singular architectural object. As articulated by Hight and Perry (2003) "innovative design does not concern the novel appearance of objects, but rather constructing new manifolds for the production of knowledge"

2. A Game of Design

Prior to undertaking the pilot study, background work has been undertaken to evaluate the technical requirements needed for a functioning multiuser virtual world, such as interface, gameplay, and communication, and to validate design choices in terms of environment, rules of interaction and competitive mechanisms. The choice of a videogame engine for the embedment of the study is rather obvious as it is the most accessible and most malleable forms of interactive 3D environment. Andreoli et al. (2005) produced an extended comparative study of several videogame engines, and their methodology was applied to the more recent generation of game engines by adding to the seven criteria enounced (graphics engine, complex models, artificial intelligence, world physics, networking, sound engine,

tools) three more practical criteria that are: cost, reputation, availability of resources. Rather unexpectedly we settled on the Source engine, popularized by Half Life 2 (2004), already present in the 2005 study.

The specific sub-framework used for the pilot study that of Garry's Mod (Newman, 2004) which released its tenth version in October 2012. Garry's mod is based on Half Life, and facilitates customization through more user-friendly means than the raw coding of the early versions. This includes but is not limited to generating complex models and modifying their attributes, and setting up complex interaction. Combined with the scripting component and the traditional map/object design tools that Source offer, Garry's mod is a flexible, efficient and stable environment to quickly design immersive and responsive virtual worlds.

2.1. THE PILOT STUDY

The pilot study uses a methodology of participant / observer to scope and prepare a specification for the future full case study. There are a wide range of tools available to manipulate complex objects, themselves subject to a mathematical model of Earth's gravity induced by the physics engine. An exhaustive list of such tools would be both interminable and irrelevant. Below is a purposeful selection of those most pertinent to the study.

- Gravity gun: the main tool. Allows to grab, move, rotate any object at any distance and in any direction.
- Weld tool: creates a constraint between two objects (or an object and the environment) that then cannot move in relationship to the other.
- Axis tool: creates a rotation axis between two objects.
- Rope constraint: creates a rope between two points on objects.
- Camera tool: creates a camera object that can be manipulated like any other. The player may switch views to the camera at any time, or display the reduced view of the camera on a Heads Up Display.
- Duplicator: a player may copy and paste an object or a group of objects anywhere on the map. One can also save the entirety of the objects in the map to spawn them in a further session, as the data is kept in the server. This permits an effective storing of the previous work sessions, and overcomes the issues of a non-persistent world.

2.2. REVERSE ENGINEERING A KIT OF PARTS

Using Source's modelling software Hammer, a series of building components have been produced that are then accessible from the object library in game. These parts are extracted from a reverse engineering process applied on Frank Gehry's

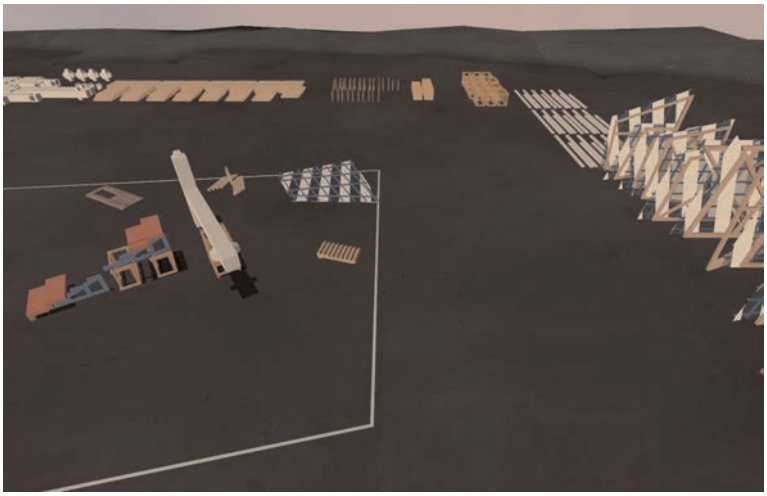

Figure 2. The kit of parts prepared in the CVE ready for designing.

2008 Serpentine pavilion. The choice of this building is embeds the collaborative process in an existing quasi competitive framework, the annual choice of architect for the Serpentine summer pavilion. Equally, it is also a convenient decision in regards to the easy readability of the building as an assembly of distinct building components. Gehry's building was fully designed in Hammer, and then disassembled into 358 pieces of 63 different shapes.

The parts are not the individual components but rather assemblies of meaningful shape and size. The design of this kit of parts as a relatively small group of simple shapes aims at considering them as boundary objects, "that allow members of different groups to come together for some common endeavour, though their understanding of the object of their mutual attention may be quite different" (Frost, 2003). Thus, future users may find in these objects a "'common ground' for their collaborative effort" (Brown and Berridge, 2001).

2.3. INITIAL FINDINGS

The participant observer study has enabled a reflection on typical design process and the implications of the use of this specific kit of parts for someone approaching the design scenario for the first time. A series of design iterations were produced over approximately two hours. During this time the architectural ambitions that arose while entering the environment and seizing the design possibilities were frustratingly out of reach. However after this initial frustration, one begins to construct more elaborate structures, reusing the first assemblies, and refining

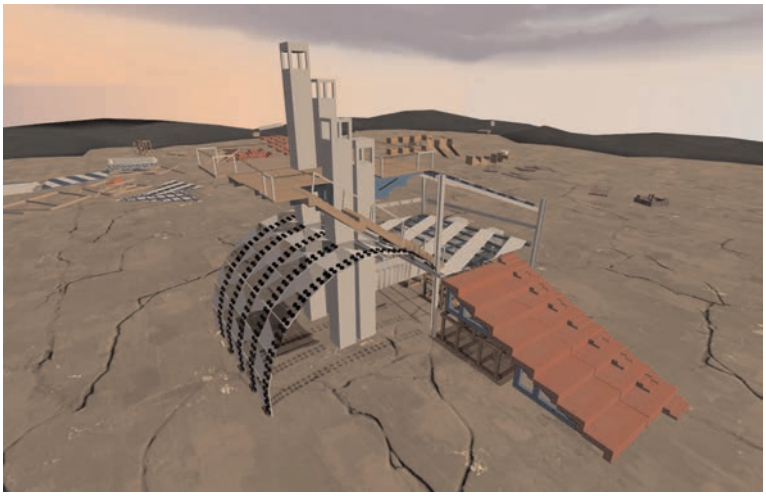

Figure 3. A design iteration from the pilot study.

skills. Limited by gravity, one must learn to build distinct parts aside of the main works in order to integrate them later. Ultimately, a reasonable pavilion iteration is put together, engaging a snowball effect: from this point the pavilion can be optimized or expanded, both for a better use of the limited parts, or one can start anew, reusing groups of parts, building systems and procedures that he learnt on the way.

An analysis based on the skill dichotomy of Merrick et al. (2010) has resulted in the following observations.

- the kit of parts fulfils its role of both a limiting resource and a motor for innovative use and reuse.
- the combination of an easy to use interface in combination with a difficult gameplay provides "an activity that is pleasurable in itself" (Juul and Norton, 2009).
- the storage and access to the precedent iterations acts well as a repository for knowledge and a foundation for erecting future designs.
- seeing every micro problem solving processes as many design puzzles that one challenges himself to solve, "enhances the potential of design capability of an individual" (Chang, 2004), that generates an understandable and satisfying aporia/epiphany cycle (Jorgensen, 2003).

3. Specifying the Next Stage

The objective is to explore the impact of a competitive behaviour within a community of designers, both in regards to the constitution and sharing of a common

knowledge base, and to the emergence of innovative problem solving. Participants will be invited to create their own iteration of a Serpentine Pavilion within the collaborative videogame environment. These iterations are assessed by a quantitative and qualitative scoring system. Quantitative for they are scored in real time against a set of programmatic requirements, and qualitative, for they are assessed by the community on more subjective criteria. It is anticipated that successive generations of iterations build up the shared knowledge pool through the display of their scores and characteristics on a leader board, and through the possibility of reviewing them within the virtual environment. Competitors will be encouraged to refine their skills, expand their knowledge and communicate their findings in order to produce innovative solutions, which will be in turn beneficial for the next generation.

3.1. THE COMPETITION

Similar to a traditional architectural competition, the study will be presented as a competition for the best design respecting the constraints of site, program and feasibility. The programmatic requirements are: a stage for small scale events, a café, and a playground. Competitors are invited to comply with these requirements to build in a virtual shared space the most compelling architecture. This will be evaluated both quantitatively through a real time points system and qualitatively by the participants. The points system will attribute a score to each aspect of the program covered by the design.

- Visibility of the stage. Extra points are granted for the area that is sheltered.
- Number of cafe tables, again with those sheltered obtaining a higher score.
- Playground size. This area must be visible by at least one café table, with extra points being granted more tables looking over the playground.

The design must score a non-null number of points in each aspect of the program to be valid. Although one can deliberately neglect one or two of the program facets and still achieve a decent score with the third one, it is clear that the three sets of scores are interdependent (e.g. if some cafe tables can see the stage, they count for the stage as well) and it is strategically beneficial to consider them altogether. The three sub-scores, the total score and an inventory of the parts used will be displayed in real time on the player's HUD. This way, one can engage with the process of optimization in the early stages of the design. Once the design is complete, three pictures are taken from generic points of view, then the digital model is saved and stored in the server for future consultation by any competitor.

In between design sessions, competitors are invited to access a web-based application that displays on a leader board all the projects. The project list can be sorted

by quantitative score (best score to worst), qualitative rating (most loved to least) or time of completion (newest to oldest). By clicking on them, one will be able to access a page where the detailed scoring, name of user, date of completion and the three pictures taken are shown. From this page's information, and the possibility to go back to the virtual to enjoy an immersive experience of the iteration, the competitor can then rate the project on three scales of one to ten against three subjective factors: aesthetics, technical difficulty and spatial quality. Once the project is rated, the competitor will be able to see both the main leader board and the dedicated project page the average qualitative score granted by the crowd. Competitors will be able to partake in the discussion specific to this iteration, in a dedicated forum page. The specification of this web-based design review system builds on the works of Hutter et al. (2011) and Van Bouwel et al. (2012) as an effective means of improving the quality of the submissions and stimulating constructive criticism.

3.2. THE COMPETITORS AND TIMELINE

The next stage of the research is to be started in early 2013 with 7 participants, all 5th year architectural design students and there will be a material prize to stimulate a competitive environment. The design sessions will be done in groups of two or more, and will be recorded. A tutorial session of two hours will be granted to all participants in groups of two, where the rules, the score and rating system will be extensively explained, and a basic demonstration of the gameplay will be shown, in the form of a short movie. Participants are expected to design at least three iterations, and this within a timeframe that allows at least two designs to be uploaded and rated between one's two iterations. Participants will be informed by mail whenever a new design is created, and will be able to rate and comment from anywhere. At the end of the study, the participants will be invited to partake in an anonymous survey focusing on the usability of the platform as a design tool, the validity of the collaborative aspect as a producer of quality content, and the validity of the competitive social setup in terms of motivation and fun.

4. In Summary

A position has developed that, based on precedent in an allied field, there is potential for architectural design to be conceived as 'open communitition'. The motivation is to validate the current efforts towards the extended implementation of collaborative online review platforms, and evaluate an open platform communal competition as a way to spur architectural innovation. A pilot study has been undertaken that has evaluated available collaborative videogame software and using a participant observer method, this has been evaluated for a future case

study. A competitive architectural game has been conceived based on the requirements of the brief for the annual Serpentine gallery. Frank Gehry's 2008 Serpentine pavilion has been reverse engineered to produce a kit of parts, and the editing tools of the game environment have been evaluated. The case study has been specified with both quantitative and qualitative criteria being considered, and will be undertaken early in 2013.

References

Achten, H. H.: Requirements for collaborative design in architecture, *Sixth Design and Decision Support Systems in Architecture and Urban Planning – Part One: Architecture Proceedings*, 1–13.

Achten, H. H. and Beetz, J.: 2009, What Happened To Collaborative Design?, *Computation: The New Realm of Architectural Design*, Istanbul, 357–366.

Achten, H., Koszewski, K. and Martens, B.: 2011, What Happened After The "Hype" On Virtual Design Studios?, *Respecting Fragile Places*, University of Ljubjana, 23–32.

Andreoli, R., De Chiara, R., Erra, U. and Scarano, V.: 2005, Interactive 3D environments by using videogame engines, *Ninth International Conference On Information Visualisation*, 515–520.

Brabham D. C.: 2008, Crowdsourcing as a model for problem solving: an introduction and cases, *Convergence: The International Journal Of Research Into New Media Technologies*, **14**(1), 75–79.

Brown, A. and Berridge, P.: 2001, Games One: Two: Three a triangle of virtual game scenarios for architectural collaboration, *in* M. C. Stellingwerff and J. Verbeke (eds.), *Accolade Architecture Collaboration Design*, DUP Science, Delft, 95–119.

Castranova E.: 2008, A test of the law of demand in a virtual world: exploring the petri dish approach to social science, CESIFO Working Paper Series, No. 2355.

Chang, T.: 2004, Supporting Design Learning With Design Puzzles, Recent Advances in Design and Decision Support Systems in Architecture and Urban Planning, Springer, Netherlands, 297–307.

Chen, R. I. and Schnabel, M. A.: 2011, Multi-touch - the future of design interaction, CAAD Futures 2011, Liège, 557–572.

Frost, P.: 2003, A real time 3d environment for collaborative design, *CAAD Futures 2003*, Tainan, 203–212.

Frost, P. and Warren, P.: 2000, Virtual reality used in a collaborative architectural design process, *Information Visualization*, London, 568–573.

Half Life 2.: 2004, Sierra Entertainment, California, USA

Hight, C. and Perry, C.: 2003, Collective intelligence in design, *Architectural Design*, **76**(5), 5–9.

Hutter, K., Hautz, J., Füller, J., Mueller, J. and Matzler, K.: 2011, Communitition: the tension between competition and collaboration in community-based design contests, *Creativity and Innovation Management*, **20**(1), 3–21.

Jorgensen, K.: 2003, Problem Solving: The Essence Of Player Action In Computer Games, *Proceedings Of Level Up – 1st International Digital Games Research Conference*, Utrecht.

Juul, J. and Norton, M.: 2009, Easy To Use And Incredibly Difficult: On The Mythical Border Between Interface And Gameplay, 4th International Conference On Foundations Of Digital Games, Florida, 107–112.

Karakaya, A. F. and Senyapılı, B.: 2006, Rehearsal Of Professional Practice: Impacts Of Web-Based Collaborative Learning On The Future Encounter Of Different Disciplines, International Journal of Technology and Design Education, **18**(1), 101–117.

Lévy, P.: 1997, Collective Intelligence: Mankind's Emerging World in Cyberspace, Plenum, New York.

Liang, C.-H. and Chang, T.-W.: 2006, Towards a playful design environment - Digame, *CAADRIA2006*, Kumamoto, 187–196.

McGonigal, J.: 2007, Why I love bees: a case study in collective intelligence gaming, in K. Salen (ed.), The Ecology of Games: Connecting Youth, Games, and Learning, The MIT, Cambridge, MA, 199–227.

Moloney, J. and Harvey, L.: 2004, Visualization and Auralization Of Architectural Design In A Game Engine Based Collaborative Virtual Environment, *8th International Conference on Information Visualisation*, London, 827–832.

Merrick, K. E., Gu, N. and Wang, X.: 2010, Case studies using multiuser virtual worlds as an innovative platform for collaborative design, *Journal of Information Technology in Construction*, **16**, 165–188.

Newman G.: 2004, Garry's Mod. Retrieved from http://garrysmod.com

Paulini, P., Maher, M. L. and Murty P.: 2011, The role of collective intelligence in design, *CAADRIA 2011*, Newcastle, 687–696.

Van Bouwel, T., Vande Moere, A. and Boeykens, S.: 2012, Archibrain: a conceptual platform for the visualization of collaborative design, *16th International Conference On Visualization Information*, London, 396–402.

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PERIPHERAL TOOLS TO SUPPORT COLLABORATION: PROBING TO DESIGN COLLABORATION THROUGH ROLE-PLAYING

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Abstract. Peripheral devices like smart phones offer an opportunity to lower the barrier to spontaneous collection and sharing of information during distributed collaboration. We have completed development of guidelines and a framework that focuses on peripheral devices in collaboration. In order to explore the design space generated by our principles, we conducted a role-playing experiment about commissioning a building, in which an "on-site" team and a "design" team were expected to find and resolve discrepancies between requirements, design documents, and the actual site. The teams were given Styrofoam panels to act as pretend smart peripherals to invoke play and help probe the design space. We found that "reflection on action" (debriefing and subsequent brainstorming) was fruitful for ideation and theorem building about interaction, but "reflection in action" failed. Yet, reflection in action, particularly with such probes, is important to capture the "mechanics of collaboration". Therefore, we are considering adapting improvisational theatre to our study of distributed collaboration.

Keywords. Collaborative design; design support tool; interactive media; role-playing; extended cognition.

1. Introduction

Collaborative design is a social and complex task involving multiple designers communicating with one another using external cognitive tools to encode, decode, and share information. During this process, small artefacts and moments of agreements often become lost or forgotten. To support collaborative design, we are developing a framework called DiNa (Huang et. al., 2011) that applies the principle of least effort during collaboration (Clark and Wilkes-Gibbs, 1986) to achieve synchronized actions, a single record of decisions, and reduced effort to record, organize and share information. Particularly, to ease spontaneous collection and

sharing of information, DiNa focuses on web-enabled smart devices that are ready-to-hand to lower the barrier to distributed collaboration by executing multiple steps of recording, organizing and sharing of information. We wish to explore the design space and evaluation methods for DiNA before making committed investments.

In this paper we report on our 'role-playing exercise' looking at the lower level "mechanics of collaboration" (Pinelle et al., 2003). In order to generate ideas, we tried role-playing a scenario, with subsequent brainstorming about the role-playing. The scenario was a simplified "play" version of commissioning a building, and involved two teams of participants – an "on-site" team, and a "design" team. Immediately after, we held a debriefing session and a bit later a brainstorming meeting. Both yielded some interesting ideas, and also some lessons that we will take into account in our future research.

2. Background

Clark and Wilkes-Gibbs (1986) adapted the idea of least-effort (Zipf, 1949) to propose that collaborators will minimize effort during presentation and acceptance of arguments. While much of today's Computer-Supported Collaboration (CSS) tools are built around file systems and structures, nevertheless, during collaboration, collaborators rely on each other to reach common understanding. In addition to the digital artefacts, we also rely on artefacts and signs that are not digitized such as back-of-the-napkin sketches, voice, facial expressions and gestures during face-to-face discussions. These are thus rarely documented. Our challenge is to lower the barrier to spontaneously record or share such information. We conducted this role-playing exercise to further understand what kind of non-digital artefacts are created, and how collaborators are interested in using them along with digital ones.

Medler and Magerko (2010) define improve[ising] as the "*creation of an artefact and/or performance with aesthetic goals in real-time that is not completely prescribed in terms of functional and/or content constraints*". The improvisers aim to achieve consensus about the scene and their roles. They define role-playing as "*the practice of group physical and spatial pretend where individuals deliberately assume a role in a constructed scene*".

Boess (2008) suggested that the role-play techniques should not be overloaded. Rather, a goal is to use the techniques flexibly. A role-playing session should be geared to either *ideation*, or *interaction*, but not both. The participants need at least an hour of preparation. Props are important, and have different roles, from prototypes to aids for understanding. The role of props could, in itself, be a research topic (Svanaes and Seland, 2004).

Morgan and Newell (2007) enabled "reflection in action" (Schön, 1983) in their employment of improvisational theatre to gather requirements for seniors-oriented

software. They used professional actors who were able to stay in character when interrupted by an audience of seniors. "*The performance of the story maintains the focus of the discussion, the characters bear the brunt of any negative comments, the audience increasingly engages and feels it's comfortable to join in and a great deal of data emerges from the discussion. The process can be recorded unobtrusively (with permission) for subsequent transcription and analysis.*" Not only were the actors prepared, this method also uses a facilitator who is familiar with the research goals.

3. Role-Playing and Brainstorming: Exploration Design Space for CSS

3.1. SCENARIO CONTEXT

The participants were asked to role-play in a building-commissioning context. Building commissioning is a highly collaborative process where building-features are verified after construction against the requirements defined throughout the design phase. Professionals from the client, constructor, and design sides systematically investigate the building on-site. They collaborate to identify if the building meets the project objectives.

As the project, we selected a recently redesigned layout of a group workstation in our lab. The participants were given the floor plans and 3D images of the layout (Figure 1) along with a set of requirements for this project. They were asked to use the provided information during role-playing to identify if the workspace area could be taken over by the client. The design and actual layout were expected to meet the requirements. In total, there were 16 requirement items. Three of them intentionally conflicted with at least one another requirement. For example, one requirement specified that a circular table should be provided in the workspace; however another requirement, at the end of the list, specified a rectangular table instead of a circular table. There were also inconsistencies introduced between the requirements, the plans and the completed layout. For example, the requirements specified planters to be placed between spaces; however, neither the plans nor the actual layout had these planters. In addition, while the requirements specified to not place any table above any HCVA register, one of the tables was right above a couple of registers in the actual layout, and at least on one register on the plan. The requirements asked for desktop lighting fixtures and the actual layout provided them, but none of the plans showed how they would be placed.

The participants were not told of the existence of these conflicts and inconsistencies. It was expected that their conversation for reaching an agreement and use of media to record their decisions as they discover them would (a) reveal new scenarios for the system being developed, and (b) help us to confirm some of the use cases we proposed for DiNa (Huang et al., 2011).

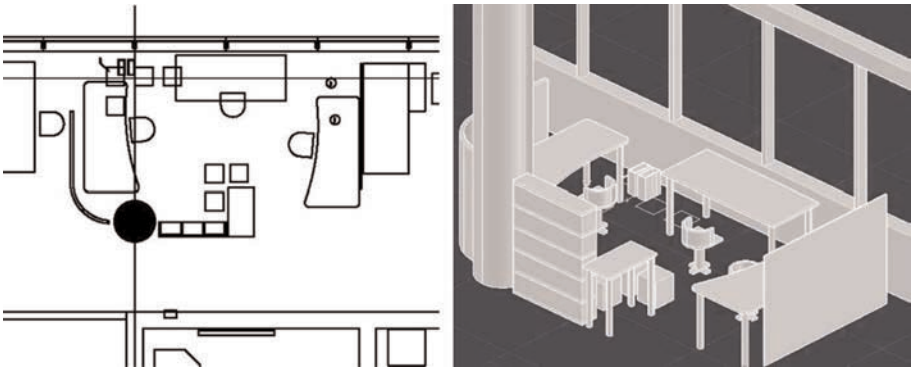

Figure 1. A section from the layout plan and its 3D image.

3.2. PARTICIPANTS AND GROUPS

The participants were members of our research group working on different projects other than DiNA. They were neither revealed the design and the purpose of the study until they were debriefed, nor did they take any active part in the scene setting. There were nine members divided into three groups: the site group, the design office group, and the observer and facilitators. Each group had three participants. The group member roles, individual goals, and their group tasks are given in Table 1. Following a brief introduction role playing, the participants were asked to create their own persona by selecting a role name and character. They wrote these after the groups were assigned and before the role-playing started. This was done to increase their engagement through their acting as if their persona were real. One participant chose to play a different gender. They were told that they groups were geographically located in different places, and there was a time zone difference. The participants were assigned to their groups based on their background and interest by the observer group.

3.3. GROUPWARE: PROPS AND PROJECT ARTIFACTS

The participants were given a set of mock-up peripheral devices resembling the available technology used every day such as smart phones, tablets, smart pens; however without any specific application implied (Figure 2). They were told these probes are capable of performing like any equivalent device.

The participants were encouraged to use these probes to record, share, and retrieve their ideas and decisions when needed. They could pretend that the props

Table 1. Participants in role-playing and their responsibilities.

Group	Real life role	Role	Responsibility
Site			
Merjan	Architect	Construction manager working for the client	This group was to confirm the workspace layout together with respect to the requirements and specifications. They were asked to record their finding and decisions. They were also asked to communicate with the office group to clarify issues.
Max	Design/ computation	Contractor responsible for delivering the project	
Karine	Collaboration/ computation	On site consultant to client	
Office			
Anita	Education/ interaction	Client and investor	This group was to confirm if the floor plans designed by the architect are meeting the client requirements compiled by the client's consultant. The client had a busy schedule. They were required to clarify requirements, receive approval for plans, and support the site during building commissioning by providing information.
Marco	Architect	Client's design consultant	
Scott	Architect	Architect designed the layout	
Observer			
O-1	Interaction Designer	Communication support	Passive participants who mainly observed role playing and took notes; assigned roles in the beginning; answer questions related to the role playing activity; manage video and audio; intervene role playing by introducing unexpected events such as missing document, disruption in communication channels, change in requirements, and arrival of missing material on site etc.
O-2	Design/ computation	Intervention	
O-3	Interaction Designer	Technical support	

could facilitate their workflow during building commissioning. Another prop was two large whiteboards as pretend-server. They were asked to post their records on the whiteboards to communicate with others (Figure 3). The groups used colours to direct their messages. Red was used to send messages from the office to site and green from the site to office. Blue and black were used to record decisions among the site and office groups respectively.

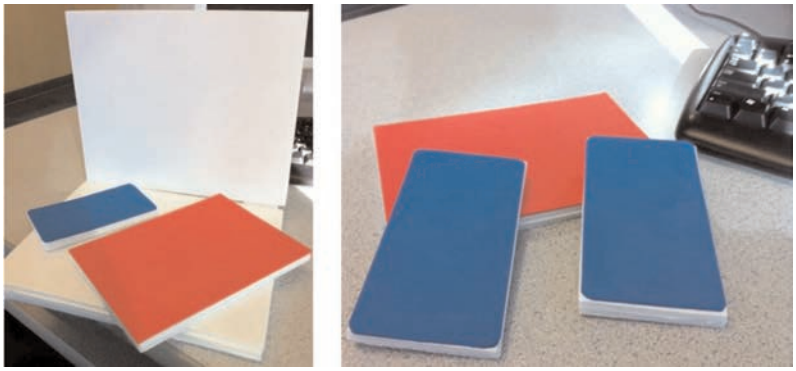

Figure 2. Props used during the role-playing.

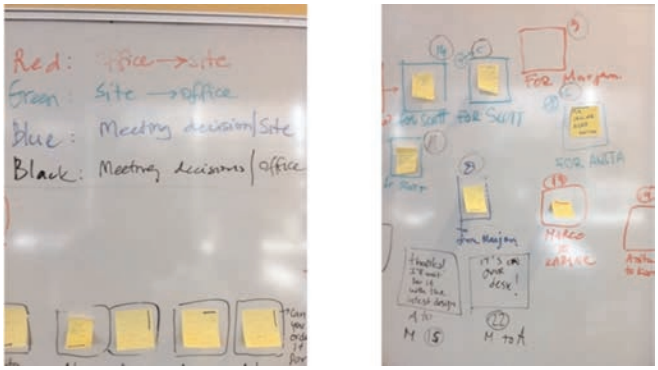

Figure 3. Whiteboard as collaboration support server.

3.4. PROCESS

The exercise took place in two sessions: role-playing and brainstorming. In the first session, the groups role-played building commissioning of the workspace (Figure 4). This session took 2 hours following 45 minutes debriefing. It started with introduction to the study, group forming, and persona definition in the first half-hour. After assigning roles, they were given the project documents by noting that they could be treated as digital documents. In addition, the participants were given the probes and post-it notes with an instruction as to how to use the white-board. The groups were allowed to make phone or video calls but only in front of the video recorders. When the observers noticed increased use of direct calls, the groups were told that the communication lines were broken to encourage them to look for other means of communication, both synchronous and asynchronous.

4. Results and Wish-List

The role-playing exercise did not directly reveal what we expected to see: use cases manifested through improvising. The site team did not use their props, while the design team barely used them. The few times that they handled the props, they used them as if in conventional rather than imaginative ways. Neither ideation nor improvisation occurred during the role-playing. Debriefing revealed that the participants were so focused on achieving their tasks that they would not take extra steps to pretend things with the props. However, this ironically confirmed the principle of least effort that we adopted in developing the DiNa framework.

The study indicated that misunderstandings could ride too long. For example, the site team misunderstood the design team's use of the symbols "X", "√", and "?" to mark the status of whether requirements were fulfilled. This issue of misinterpretation was not identified except by intervention; and came to light only upon gentle prodding by a facilitator, whereupon clarification communications ensued. On the topic of misunderstanding, debriefing revealed that the participants had been unclear about their responsibilities and hierarchy, but they were too busy with their tasks to seek clarification from the facilitator. This convinced us that

Figure 4. (TL) Design office; (TR) Site team; (BL) An issue is being raised on the whiteboard; and (BR) an observer interrupting site team to clarify their move.

DiNa needs a mechanism to watch for clues of misunderstanding, and query collaborators about them. For example, Anita (the busy client) had been promised to be kept updated, but the promise was not fulfilled. She then studied the history of communications on the whiteboard as a way to update herself about what was going on. If DiNa knows that updates are expected, then a timer could inform those responsible. Anita used numbering and arrows to trace conversation history using visuospatial clues. One of the ideas that came up in the debriefing was the need to be nagged about hanging promises.

The site team members preferred working on their individual notes rather than keeping a shared document. Most of the content of these notes included brief short sentences, abbreviations, sketches and diagrams, which sometimes required further clarification when discussed with other members.

The conference call at the end of the session resolved some issues. During the call, Scott tried to peek at Max's document, which Scott forwarded him earlier. He said that the document he sent to Max was not the version he had during the conference call. He needed to look at his 'notes' on the (paper) analog document. An important finding was that the subject of communications appeared to be issue-based, while documents supported the issues. The supporting documents were not always included in the communications, what referenced when needed. This is consistent with our approach in DiNa.

Max (the contractor) suggested supporting task breakdown structures such as Work Breakdown Structure that usually serves as a master reference in collaboration. A phone call about an issue could collect the caller IDs, the time, and the geo-location. The phone could recognize that the callers are work partners, and automatically record the conversation and upload it (unless aborted). The DiNa system would apply team-generated tags and organizing metadata (including for associating dependent areas of work), and notify pertinent other collaborators. All this activity could be mapped to a Work Breakdown Structure master reference.

In addition, the brainstorming session revealed a 'wish-list' from a CSS:

- Instant information on an activity progress without the complexity of a project management system.
- A way to turn ordinary surfaces into shared work surfaces, e.g. point an iPhone camera at a desk, indicate via gesture the focus area on the desk,
- Message time line that can be visualized by issue, participant, project, meeting, priorities etc.
- Ability to browse sketches and notes during and after the meetings by issue not by document,
- Use digital technology to combine analog and digital resources.
- Enhance reality to match digital views in spatial contexts. The camera of a smart phone or tablet that knows its location and orientation could obtain from the system

information for enhanced reality. Multiple phones could be coordinated to take measurements, exchange team specified information by bumping them together. Multiple pictures can be used to create 3D models.

5. Discussion and Conclusions

The first study we conducted to receive feedback from a potential user group for DiNa revealed interesting findings for both the system and the role-playing method. For DiNa, we received confirmation on our initial assumptions, such as the importance of issue-based collaboration, easy-to-use peripheral devices with minimal cognitive load, flexible and almost constraint-free collaboration support etc. During the role-playing exercise, we did observe much technology improvisation, but reflection on the role-playing invoked a rich set of features for DiNa.

The participants' comfort with role-playing and improvisation was very uneven. On one hand, one participant could not imagine using a different name, let alone a different character, while another happily played both a different gender and a different sexuality. Several could not see any benefit of playing a fictional character. Similarly, improvisation depends on the actor being secure and resourceful in the role. Our participants needed more preparation, plus the staging and action needed to better afford "reflection in action". Thus we could learn from Morgan and Newell (2007) that better prepared role-players (in role-playing) would response better to unexpected interruptions. While they hired professional actors, in our case we needed domain expertise in building design and commissioning. A brief training on role-playing, possibly by an actor, could better prepare the participants.

During role playing, the participants were engrossed in problem solving through their tasks; too engrossed to improvise. We wanted to study the problem solving, which is at odds with the participants being well enough versed in some script to depart from it. Boess (2008) indicated this dichotomy: that ideation and interaction should not be tackled in the same scenario. But it is not the problem solving per se that we are interested in, being that much is already known about collaboration. Rather, we were looking at the lower level "mechanics of collaboration" (Pinelle et al., 2003). Therefore, we could let our "actors" know the script, reserving some participants to be a critical audience, and one to be a facilitator. The issue then is how to encourage improvisation at the mechanical level. Boess's (2008) concluding focus on the role of props in role-play as a research topic underscores this issue.

In a following study, we plan to build paper and digital mock-ups following what we learned from the study and perform a "groupware walkthrough" (Pinelle and Gutwin, 2002) with them. For example, DiNa envisions supporting mark-up

projection on analog documents from digital records without a complete digital copy of analog documents. Current smart-pen technology can easily facilitate this. Managing two groups working independently was very confusing. The follow up study should focus on one group with well-defined roles and tasks. We will also refine our role-play research method, focusing on staging acts of communication, and finding ways to facilitate the use of "props". Our research goal is to implement the first prototype of DiNa, based on what we learned from these studies, and what we will learn from the next iteration. Ultimately, the implementation will help us to test the validity of our approach.

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References

Clark, H. H. and Wilkes-Gibbs, D.: 1986, Referring as a collaborative process, *Cognition*, **22**(1), 1–39.

Hutchins, E.: 1995, *Cognition in the wild*, MIT, Cambridge, MA.

Huang, A. T., Erhan, H. I., Nasirova, D., Woodbury, R., Kozlova, K. and Botta, D.: 2011, Collaboration Workflow Simplified: Reduction of Device Overhead for Integrated Design Collaboration, *Computer Aided Architectural Design Futures 2011*, Liege, Belgium, 591–602.

Zipf, J. K.: 1949, Human Behaviour and the Principle of Least Effort: an Introduction to Human Ecology, Addison-Wesley.

Morgan, M. and Newell, A.: 2007, Interface between two disciplines-the development of theatre as a research tool, *Human-Computer Interaction: Interaction Design and Usability*, Springer, 184–193.

Pinelle, D. and Gutwin, C. (2002). Groupware walkthrough: adding context to groupware usability evaluation, *CHI'02 Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM, New York, 455–462.

Pinelle, D., Gutwin, C. and Greenberg, S.: 2003, Task analysis for groupware usability evaluation: Modeling shared-workspace tasks with the mechanics of collaboration, *ACM Transactions on Computer-Human Interaction (TOCHI)*, **10**(4), 281–311.

Schön, D.: 1983, *The reflective practitioner*, Basic books, New York.

Boess, S. U.: 2008, First steps in role playing, *CHI '08 Extended Abstracts on Human Factors in Computing Systems*, ACM, New York, 2017–2024.

Medler, B., and Magerko, B.: 2010, The implications of improvisational acting and role-playing on design methodologies, *CHI'10 Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM, New York, 483–492.

Svanaes, D., and Seland, G.: 2004, Putting the users centre stage: role playing and low-fi prototyping enable end users to design mobile systems, *CHI'04 Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ACM, New York, 479–486.

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FABPOD: AN OPEN DESIGN-TO-FABRICATION SYSTEM

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Abstract. Digital workflows from the design to the production of buildings have received significant recent attention in architectural research. The need for both integrated systems for design collaboration (Boeykens and Neuckermans, 2006) and clear and flexible communication flows for non-standard fabrication outcomes have been identified as fundamental (Scheurer, 2010). This paper reports on the development of a digital "design system" for the design and prototyping of an acoustic enclosure for meetings in a large open work environment, the *FabPod*. The aim was to keep this system open for temporal flexibility in as many aspects of the finalisation of the design as possible. The system provides novel examples of both integrated collaboration and clear communication flow. (1) Acoustics is included as a design driver in early stages through the connection of digital simulation tools with design models. (2) Bi-directional information flows and clear modularisation of workflow underpins the system from design through to fabrication and assembly of the enclosure. Following the completion and evaluation of the *FabPod* prototype, the openness of the system will be tested through its application in subsequent design and prototyping iterations. Design development will respond to performance testing through user engagement methods and acoustic measurement.

Keywords. Digital workflow; prototyping; acoustic simulation; collaborative design.

1. Introduction

The *FabPod* is the second iteration in a progression of research exploring the acoustic properties of doubly ruled, specifically hyperboloid surfaces. The

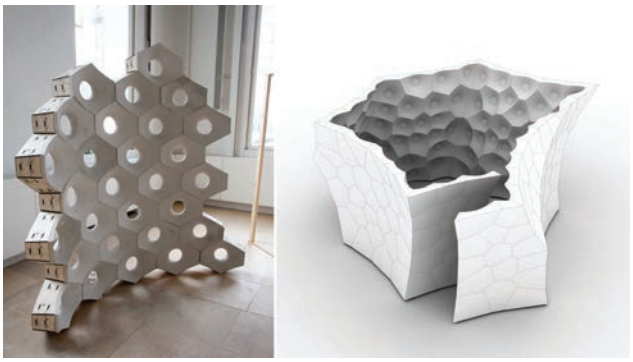

Figure 1. The full scale wall constructed in the RAS SmartGeometry cluster (left), and a rendering of the proposed FabPod prototype (right).

research stems from a hypothesis, based on anecdotal evidence from Antoni Gaudí's Sagrada Família church, that hyperboloids are effective diffusers of sound. This hypothesis was initially tested by constructing a prototype wall from hyperboloid shaped plaster bricks as part of the *Responsive Acoustic Surfaces* (RAS) cluster at SmartGeometry 2011 (Burry et al., 2011) (Figure 1, left). Building upon the promising outcomes of these experiments, in this iteration we explore whether hyperbolic surfaces can be employed to create a meeting room that satisfies auditory and acoustic criteria – the *FabPod* (Figure 1, right).

Both the collaborative nature of the project as well as the opportunity for an ongoing series of design iterations led to the conception of a generic "design system". The system itself was prototyped as part of its development before application to the full-scale fabrication process. It was underpinned by a holistic conception of a workflow, from early schematic stages through to the complete fabrication of the prototype. A series of digital tools are central to the workflow, however it is also designed around manual assembly processes for quality of finish. In such contemporary projects engaging design processes, geometry and fabrication technologies which are non-standard, it has been well documented that digital workflows have significant impact on both the richness of design potential and quality of the built outcome (Marble, 2012).

2. Background

2.1. RESPONSIVE ACOUSTIC SURFACES

The *Responsive Acoustic Surfaces* (RAS) cluster at *SmartGeometry 2011* demonstrated the potential for acoustically reflective surfaces to act as sound diffusors

when they have a hyperboloid shape (Burry et al., 2011). As part of this cluster a full scale wall prototype was developed from plaster hyperboloids supported by a plywood frame. The wall was semi-circular in plan, a shape known to be acoustically challenging since all the reflected sound is concentrated at a central focus point. However, the wall with this surface articulation had a perceptible impact on the diffusion of sound when compared to a smooth wall of the same overall curved geometry. The hyperboloids were distributed in a regular pattern across the wall in order to simplify both the acoustic measurements and the construction of the plywood frame (by standardising the brick shape). Even though the wall shape and hyperboloid distribution was relatively straightforward, the researchers still encountered challenges both in calculating the intersections of the hyperboloids and designing a satisfactory construction paradigm.

While the hyperboloid wall from the RAS cluster was ideal for demonstrating sound diffusion, research by Peters and Olesen (2010) suggests sound diffusion can be improved further in practice by minimising periodic tessellation of the surface pattern. This was tested through the 1:10 scale modelling in the workshop to test scattering coefficients.

2.2. THE FABPOD BRIEF

The physical context for the *FabPod* exercise is an open knowledge work environment within a new faculty building in the University. The architectural brief called for a space that could comfortably seat 8 people. Complete acoustic privacy within the enclosure was not required. Rather, the brief was to provide a significant barrier to sound transmission into and out of the meeting area and an internal acoustic that was conducive to small meetings. The research team proposed that a design that combined partial acoustic absorption with a degree of sound scattering would be an appropriate response to this brief. It should provide some sound reduction close to the source, good speech intelligibility without loud and quiet spots and a space that would remain bright and lively rather than suffering the deadening effect of excessive sound absorption (Bradley, 2009). By deploying absorbing materials and forms for sound scattering on the outside of the structure, it should improve the auditory experience of the surrounding workspace (Petersen, 2008).

Importantly, the brief was based on the understanding the project proposed a prototype, a structure that might be evaluated to extend the project to further briefs and similar structures. The brief was in some regards highly generic, situated within a common context. It was clear that a design system was required that was sufficiently flexible and open to be applied to range of scenarios, a system that could be used to design a series of unique but related structures in response to the research findings from the evaluation of the first.

3. Aims – Temporal Flexibility in Design

Common to standard architectural projects, the most fundamental requirement of the workflow is the clear and consistent flow of information in a 'downstream' direction (Williams et al., 2011). This follows a chronological project sequence from early design proposals, through to models with greater levels of detail and the further communication of the required information for fabrication.

Contrasting such a linear model, the FabPod project required temporal flexibility in order to address the acoustic design imperatives as well as facilitate the desired fabrication quality. The central aim was the ability to defer decisions where further research and testing would be of benefit, without halting the work on other aspects of the project. This was dependent on a workflow which would incorporate a very clear set of geometrical constraints as well as programmatic considerations, materiality, and fabrication and construction constraints. It was a requirement that information be communicated upstream in two broad forms: (1) as knowledge resulting from acoustic simulation fed back into early stage design and; (2) as a series of parameters and limits relating to the fabrication, in order that the design met a series of requirements consistent through the process (Figure 2).

While such a design system shapes a clear design space, it should allow significant design flexibility within this constraint system. For instance, while the final form was constrained to a given number of types, in this case comprised of intersecting segments of spheres, further detail of the room should be able to be deferred until the commencement of fabrication, as detailed custom components, assembly and fabrication design are already fully developed. Once identified, such constraints provided significant temporal flexibility. However, this also demanded the identification of constraints which were sufficiently broad enough so as not be overly deterministic both architecturally as well as in significant variation relating to performance criteria, here primarily acoustic.

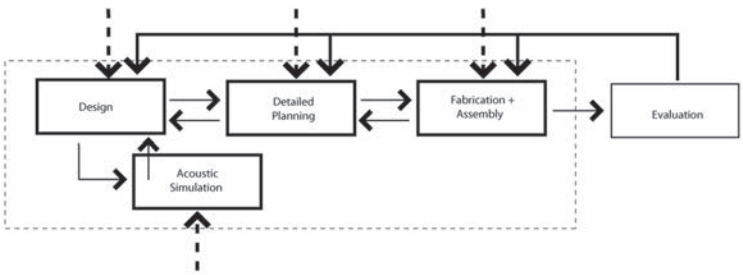

Figure 2. The broad workflow elements and information flows required for the FabPod.

The research did not seek to either propose or engage a holistic software environment in which all aspects of the design exercise could be integrated. While there has been wide spread speculation on such integrated packages and so-called 'collaborative platforms' proposed (Boeykens and Neuckermans, 2006), a package suitable to the project's drivers and providing adequate flexibility could not be identified. We aimed instead to connect the software packages and specialised tools of the involved collaborators within the workflow.

Underlying this was a strong consideration of how the workflow might be modularised. The aim was for a collection of components which could be easily adjusted, exchanged or even bypassed as required without disrupting broader project continuity. The conception of such a modular workflow requires the clear definition of appropriate interfaces defining inputs and outputs. These must be intelligently conceived so as not to be overly complex but to allow for a degree of flexibility, even if this involves maintaining a degree of redundancy (Williams et al., 2011). Further research has shown that the division of models into modular stages greatly improves the overall legibility of a project (Davis et al., 2011).

4. Methodology – The Design System

4.1. ACOUSTIC SIMULATION IN DESIGN

We developed a series of design tools for the early design stages. These comprised parametric models governed by the generic rules of the geometric system of intersecting spheres and hyperboloids. The models were organised according to a clear set of processes for an individual designer to address the overall form, surface patterning and distribution of surfacing materials across a given design geometry (Figure 3). They respond to a common structuring of acoustic simulation software in which building geometries are commonly presented as simplified geometries, to which coefficients are attached to represent the acoustic properties such as the reflection, absorption and scattering of sound.

The first of these models addressed the overall form of the enclosure. This utilised the geometric constraint of planar intersections between hyperboloids to identify a finite set of design spaces which might utilise either planar or spherical geometries to set out the overall form of an enclosure. The acoustic properties of planar surfaces, including those with highly articulated surface geometries, have been well researched and so we focused on spherical geometries.

The second model created the surface pattern. The distribution of hyperboloid surfaces was controlled by the distribution of a set of points, each corresponding with the position of centre point of the collar of the circular hyperboloid with the parent surface. The solution space for distributing the

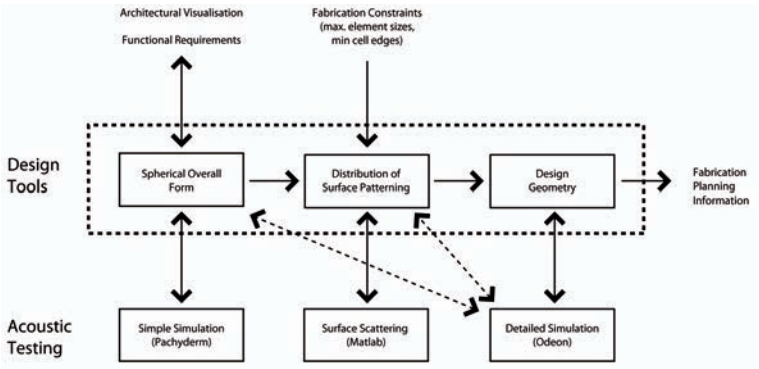

Figure 3. The three design models, their interactions with acoustic packages and fabrication constraints.

pattern points was so discontinuous and in the end we used a UV mapping to wrap a two-dimensional distribution of points onto the surfaces. The pattern was then created with a spherical voronoi algorithm written specifically for this project (http://parametricmodel.com/SphericalVoronoi/67.html).The final model transforms the planar pattern into hyperboloid geometry. This involves both generating and trimming the hyperboloids to create a single undulating surface. In the RAS workshop it was found that intersection algorithms built into Rhino, CATIA, and OpenCascade would often take many minutes to trim the hyperboloids, which limited the speed of design iterations. In *FabPod* we instead derived a formula for finding the intersections of the hyperboloids with an averaged intersection plane. This was achieved by taking the formula for a hyperboloid:

$$\frac{x^2}{a^2}+\frac{y^2}{a^2}-\frac{z^2}{c^2}=1 \tag{1}$$

And the formula for a line:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} i \\ m \\ p \end{bmatrix} + \begin{bmatrix} j \\ n \\ q \end{bmatrix} \cdot t \tag{2}$$

And then eliminating x,y,z and solving simultaneously for t:

$$t = \frac{-2\cdot(c^2ij + c^2mn - a^2pq) \pm \sqrt{(2c^2ij + 2c^2mn - 2a^2pq)^2 - 4\cdot(c^2j^2 + c^2n^2 - a^2q^2)\cdot(c^2\cdot(i^2+m^2) - a^2\cdot(p^2+c^2) - 1)}}{2c^2(j^2+n^2) - 2a^2q^2} \tag{3}$$

4.2. FABRICATION WORKFLOW

Underpinning the fabrication of the Pod is the division of the system of ‘cells’, hybrid components which can be fabricated individually and subsequently assembled in place. This system is a direct extension of that utilised in the RAS workshop and considered a successful fabrication for its suitability to manufacturing from standard material sizes and which can be handled by a single person. Each cell comprises a timber frame with hyperboloid and planar faces on opposing sides (Figure 4). In the final assembly, these hyperbolic faces are the visible and are the acoustically designed surfaces of the pod. The frame, though hidden when complete, provides structure, geometric definition for ease of fabrication and assembly as well as acoustical separation through the provision of mass.

The final pod is comprised of a series of cells with simple bolted connections between frames. Allowances were needed for machining and fabrication tolerances between cells and these were included as ‘spacers’, the thickness of which could be adjusted up to 0.5 mm, a measure typically associated with furniture. In the final assembly these pieces are read as shadow lines.

It was vital to model the assembled components as a full digital prototype to check the outcome – the exact geometrical relationships are difficult to predict. This would also be used as the basis for extracting the fabrication and construction information for cutting and forming. To avoid burdening the design model with the large amounts of information needed for the detailed prototype, an independent model was developed in *Dessault Systemes’ Digital Project*. Design data was communicated from the design model to it through a neutral comma-separated within an agreed interface. This model was a key aspect of the larger modular workflow, however, further details are outside the scope of this paper.

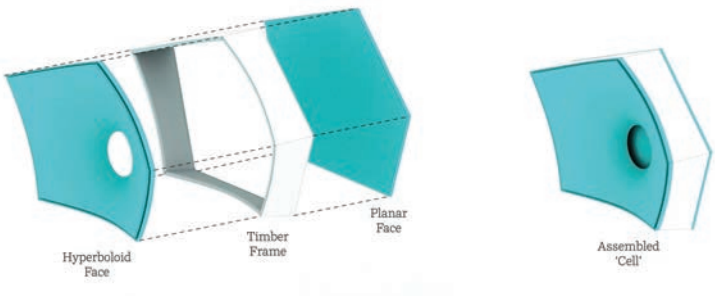

Figure 4. The basic components for the fabrication of a ‘cell’.

Taking geometry from both this detailed model, as well as geometrically simple items from the design model, a modular workflow was created to extract information required for the fabrication and assembly of components.

5. Results

Broadly, the workflow has proved sufficiently open to meet project ambitions to this stage. A week-long workshop intensive engaging students and practitioners with researchers explored an expansive set of design possibilities. The following week, the fabrication of the full-scale prototype commenced. The enclosure was successfully fabricated and assembled within the proposed timeframe of four months.

5.1. ACOUSTIC SIMULATION DRIVING DESIGN

The design workflow, bringing together a series of parametric models with several acoustic software packages including *Pachyderm*, a plugin for *McNeel Rhinoceros* and *Odeon*, a commercial room acoustics package. This provided an accessible and rapid generation of proposals at varying levels of detail and the testing of acoustic implications. As the models were parametric, the feedback at each stage could be rapidly incorporated allowing the model to be iteratively developed towards acoustic performance criteria, including targets for reverberation time and surface scattering coefficients. Alternatively, if acoustic simulation showed the design had limited functional characteristics, the divisions between stages made it easy to revert back to a prior design state and revisit the underlying causes. This ability to push the design backwards and forward between stages of development meant that the design team had the best knowledge and feedback to make these decisions.

Further, since each model functioned independently with well-defined interfaces, an instance could be easily replaced without disrupting the downstream or upstream models (provided the replacement model accepted and produced the prescribed geometry). As a key example, we experimented with a range of techniques for distributing the points that generated the patterned surface. We tried everything from dynamic relaxation, to circle packing, to swarming algorithms. Each time we tested a technique we swapped it into the overall design chain, which was simply a matter of importing the required geometry from the previous stage and creating the prerequisite geometry of the subsequent stage. If a monolithic model had been used, making such major changes to very fundamental aspects of how the design was created would have required significant modification of the model.

The focus on developing sophisticated and computationally cheap algorithms for key problems allowed for the design and feedback loop to occur within an acceptable timeframe. A maturing of this system could provide for the further

automation of key measurements to reduce this time. A level of this automation could conceivably be achieved without compromising the temporal flexibility of decision making, for instance a chain automating the calculation of sound reverberation times at given locations.

5.2. PROTOTYPING FLEXIBILITY

We have been able to apply the workflow to complete the prototype despite shifting logistical requirements and prototyping decisions made late in the process (Figure 5). We achieved the desired tolerances of less than 0.5mm and the material qualities and finishes are to a satisfactory level for the project leaders.

Significantly, the modular workflow allowed for the deferral of key decisions to accommodate for both the testing of component detailing and open logistics in the final delivery. The former of these is demonstrated by the development of assembly details for the timber frames. Holes in the central plate of the frame, found to be needed for access for assembly and fixing in construction, required additional laboratory transmission testing to clarify their impact on acoustic transmission. Details of the frame were left open to allow for testing of the machining tolerances and the assembly of parts within acceptable tolerances.

An example of the latter aspect, open logistics, was the final selection of a machine capable of achieving 5-axis cuttings at varying angles. While several machines had been identified, their availability and ability to handle the technical requirements could not be confirmed until well into the prototyping process. It has been well noted that CNC machines from different vendors require different G-code formats (Scheurer, 2010). As the machine was not selected until late in the process, tool paths were encapsulated in the generic APT file format which could be post-processed for a specific machine.

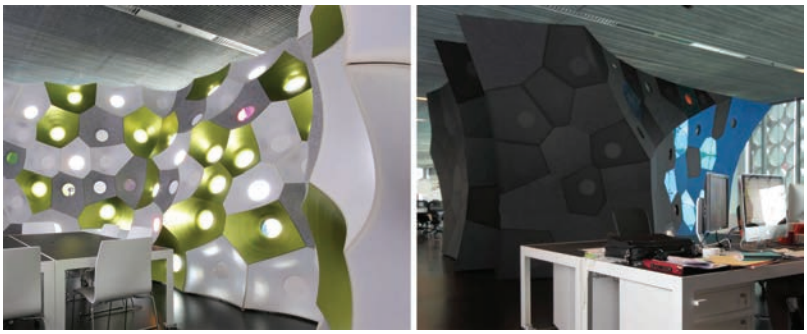

Figure 5. Images of the completed FabPod prototype.

6. Conclusion

This paper presents a modular workflow for a design system that is open in providing for temporal flexibility in as many aspects of the project as possible within a given constraint system. Most significantly, the workflow allows for the integration of acoustics as a design driver and the deferred finalisation of overall form and surface patterning to allow for as much acoustic testing and understanding of acoustics as possible. Testing and trials for the physical detailing of the FabPod also involved a high degree flexibility to allow for a refinement and development of fabrication strategies. The modular workflow allowed for aspects to be altered or exchanged without compromising the overall outcome of a full-scale prototype. This workflow will be further evaluated in application to future Pod design development and prototyping. The design will be developed in response to auditory and ethnographic testing through interaction with users and acoustic measurements on site.

Acknowledgements

John Cherrey contributed significant expertise to the project outside the scope of this paper. Further, a group of 16 students and 4 practitioners were engaged in a five-day intensive workshop and subsequently in fabricating the prototype. The project received funding from The Property Service Group and The Design Research Institute at RMIT University as well as The Australian Research Council through its support of the ARC Discovery Grant *Challenging the Inflexibility of the Flexible Digital Model.*

References

Davis, D., Burry J. and Burry, M.: 2011, Understanding Visual Scripts: Improving Collaboration Through Modular Programming, *International Journal of Architectural Computing*, **9**(4), 361–376.

Williams, N., Stehling, H., Scheurer, F., Oesterle, S., Kohler, M. and Gramazio, F.: 2011, A Case Study of a Collaborative Digital Workflow in the Design and Production of Formwork for 'Non-Standard' Concrete Structures, *International Journal of Architectural Computing*, **9**(3), 223–240.

Peters, B. and Olesen, T. S.: 2010, Integrating Sound Scattering Measurements in the Design of Complex Architectural Surfaces, *Future Cities*, ETH Zurich, Switzerland, 481–491.

Burry, J., Davis, D., Peters, B. Ayres, P., Klein, J., Pena de Leon, A. and Burry. M: 2011, Modelling hyperboloid Sound Scattering: The Challenge of Simulating, Fabricating and Measuring, *in* C. Gengnagel, A. Kilian, A., N. Palz and F. Scheurer (eds.), *Computational Design Modelling*, Springer, 89–96.

Bradley, J. S.: 2009, A new look at acoustical criteria for classrooms, NRCC-51320, National Research Council Canada.

Marble, S. (ed.): 2012, *Digital Workflows in Architecture: Design – Assembly – Industry*, Birkhauser, Basel.

Petersen, C. M.: 2008, Limiting Annoying Noise in Open-plan Offices, *Joint Baltic-Nordic Acoustics Meeting 2008*, Reykjavic, 11 pp.

Scheurer, F.: 2010, Materialising Complexity, *Architectural Design*, **80**(4), 86–93.

Boeykens, S. and Neuckermans, H.: 2006, Improving Design Workflow in Architectural Design Applications, *International Journal of Architectural Computing*, **4**(4), 2–18.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 261–270. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

QUOKKA: PROGRAMMING FOR REAL TIME DIGITAL DESIGN PLATFORM

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Abstract. This paper introduces an interactive 3D scanning tool (Quokka) that generates real time point clouds and surfaces in a design program (Rhinoceros). It explains the use of this tool through a detailed experiment, suggesting a new mode of design using a dynamic, three-dimensional grid.

Keywords. Real time design; real time feedback; interface; Quokka; reconstructing surfaces; dynamic point cloud.

1. Introduction: Designing in a Dynamic Cloud

Within the history of design computing, architects, designers, and engineers have investigated ways to create a seamless interface between reality and the virtual world. Recently design generation has increasingly migrated from the tangibility of the physical model toward the digital realm. While this sea change has added significant benefits to the design process, and the differences have significantly decreased, there still seems to be a gap for architects who are attempting to smoothly mediate between these two states.

One method of alleviating this disparity between the physical and the digital during the design process has been the introduction of 3D scanning. This method, which assists in gathering existing site conditions and site context, has developed quickly in the last decade with the use of portable 3D scanners. Land surveyors are using these to scan terrains and regenerating them digitally as point clouds, and preservationists are implementing their use to reconstruct historical facades (Yang et al., 2011).

The problem of introducing scanners into routine practice for both the professional architect and student are twofold; they are cost prohibitive, and, more importantly, they require additional knowledge of specific programs and procedures which are not directly connected with traditional design programs that

architects are familiar with. Designers need to use special plug-ins to import the point cloud into a design program such as AutoCad and Rhino. Recently, Autodesk has bridged this gap by enabling designers to import point clouds in Building Information Modelling (e.g. Revit 2013), allowing architects to import point clouds and re-mesh the surface generated from surveyor scanners into the design program. However these solutions simply provide a literal snapshot of a site or object within one moment in time. As a result, the ability of using point clouds is still limited by the static nature of the previous processes. Real time scanning, used in a generative design process, can allow for innovation applications such as vector motion design driven by surface curvature. This will result in achieving a closed real time design feedback loop.

This paper not only presents an inexpensive way of reality capture using Microsoft Kinect as a real-time 3D scanner, but it also proposes a tool to rearrange a point cloud generated from the 3D scanning process in order to create a dynamic surface using an add-on for Grasshopper and Rhinoceros we developed called Quokka. The use of these two innovations suggests a novel method for designing and interacting with a *dynamic* three-dimensional grid in Rhinoceros in *real time*.

This research illustrates how Quokka allows designers to use Kinect in a parametric program to scan surfaces, digitise designed objects, capture real time data, deal with human interaction and even reverse engineer physical models. The paper explains the technical methods of developing this tool and demonstrates an architectural application that reconstructs a digital surface using a physical surface as dynamic input for generative tools. The significant thing about this method is that designers will be able to modify those generative digital surfaces by physically manipulating a surface, model, or other physical objects in real time. This process adds the possibility of another significant dimension to the design process – the possibility of designing with (real) motion and movement.

2. Precedents

2.1. THE REALITY/VIRTUAL INTERFACE

Since John Frazer's canonical project of the Universal Constructor (Frazer, 1995), architects and engineers have attempted to bridge the gap between actions, behaviours, and movement in reality with representations on the computer screen. Another project called Graspable User Interface conducted by Fitzmaurice et al. (1995) addressed similar issues by creating a collection of input devices called 'bricks' which could be moved within a defined horizontal surface called ActiveDesk. Rather than using a mouse and cursor, it was hoped that the bricks, coupled to virtual counterparts, could create physical spaces with corresponding digital versions.

The Tangible Bits project by Ishii and Ullmer (1997) conducted at the MIT Media Laboratory was another attempt to expand the notion of an interface between the real and digital world (at the time referred to as 'cyberspace') using what the researcher described as Human Computer Interaction (HCI). Rather than being simply limited to the computer screen and mouse as input devices, the researchers were able to re-interpret the virtual/reality boundary by imagining a metaDESK, transBOARD, and ambientROOM as a new means in which to translate real-world data.

2.1.1. 3D Scanning

Using GIS, a laser scanner, computer projection, and a clay tableau, researchers of the Illuminating Clay project created yet another alternate interface. The set-up would allow landscape analysts to directly manipulate the surface of a landscape and view possible outcomes, however this process, as the researchers concluded, did not offer a fine type of visual accuracy, was very slow, and extremely expensive (45,000 euro) considering the final outcome which was conducted using a simulated environment from a projected image, not from a real-time source. (Piper et al., 2002).

In 2010, the Scanlab at The Bartlett conducted a series of projects centred on the use of the 3D scanner as a tool in design and in collecting data (Trossell and Shaw, 2011). The projects ranged in scope from the scanning of physical objects and existing site conditions and their calibration in digital models, to the collection and analysis of environmental and urban data. These projects did not use Kinect, but rather employed a self-built 3D scanner and open-source scanning software.

2.1.2. Kinect in Architecture

Game technology has recently introduced useful devices that can bridge this gap of obtaining information from the physical world and importing into digital data in real time. The Microsoft Kinect was developed for the Xbox 360 video game console as a motion-sensing device which can gather motion data of up to two players; allowing them to interact with games through the tracking of player body position. (skeletons)

There are many recent publications dedicated to hacking the Kinect sensor (Borenstein, 2012; Kramer et al., 2012; Webb and Ashley, 2012), however few are dedicated specifically toward its application in architectural design. A recent research using Kinect as a 3D scanner linking physical models to virtual ones can be seen in Salim et al. (2011). Here researchers, building on the set-up of the Illuminating Clay project, re-examined the topic of Tangible User Interface by

installing a Kinect sensor suspended alongside a projector above a horizontal surface, creating a scenario were a display, based on a stream of real-world data, was projected onto a physical model. While this experiment used Kinect for its experiment, the approaches and outcomes are different. In the Quokka experiment, long processing times for the end user were avoided by writing in C# a direct add-on for Grasshopper in Rhino. In addition, Quokka enables a quicker, streamlined method in that it does not require the many calibrations and coding which are not necessarily part of the knowledge base required from architectural students and practicing architects.

These interface precedents consist of almost two decades of research and have, either directly or indirectly, contributed to the development of knowledge in this area. However the experiments used unique, very elaborate, or expensive equipment with results and methodologies that are not widely practiced within the discipline of architecture today. The Quokka research was developed using existing, well-known architecture programs, and explored the potential of widely available, inexpensive 'off-the-shelf' game technology for architectural use. More importantly, our experiment resulted in a method of receiving feedback in real time.

2.2. WHAT IS QUOKKA?

Quokka is an add-on to Grasshopper that allows the use of Microsoft Kinect in Grasshopper for Rhinoceros (Figure 1). It provides both depth point cloud data and player skeleton data (Figure 2). A Software Development Kit (SDK) for Microsoft Windows (Windows) was released in June 2011. This SDK allows, among other functions, the accessing of depth data and the body position tracking of up to two players. The depth sensor consists of an infrared laser projector combined with a monochrome CMOS sensor that captures video frames in three dimensions. A 3D scan was produced through the use of Kinect, which captured the surface data by locating of the surface points and transforming them into a point cloud. Quokka enables the use of Kinect as a real time 3D scanner, and gives the designer the following options:

- Output of depth point cloud data in real time.
- The use of a custom scale with a default of the Australian architecture standard of millimetres.
- Toggling of depth points associated with either players or background.
- Setting the granularity of point output.
- Allowing ranges to be set to isolate subject surfaces and objects.
- Output of skeleton joint points and bone lines for up to two players.
- Toggling of output of joints and bones.

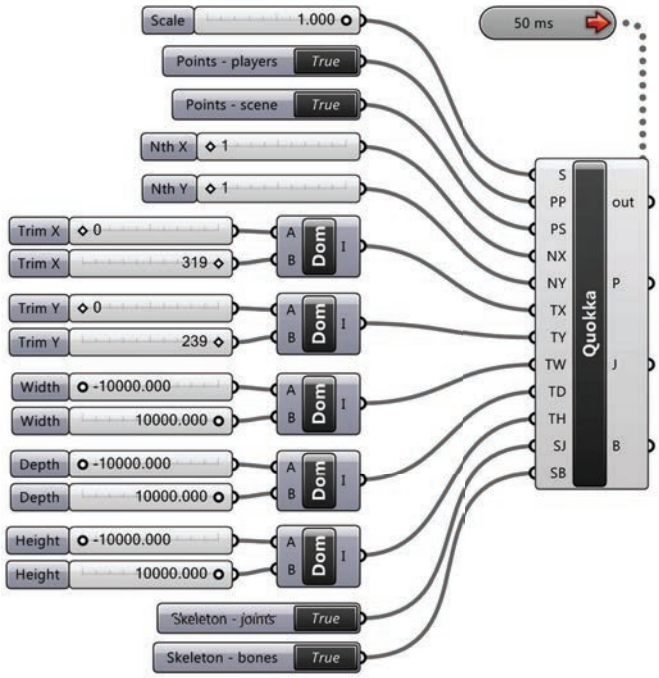

Figure 1. Quokka and inputs in Grasshopper.

Figure 2. Output of player and background points, player points only, background points only, and skeleton data.

3. Equipment Set-up and Method

In the experiment pictured above there are four main components: a physical scaled model with a tower containing a flexible surface (in black with white grid and Quokka logo), the digital version in Rhino of the model, a Kinect scanner, and the computer with Rhino, Grasshopper, Quokka add-on, and Kinect driver

Figure 3. The photo of the scanning set-up, which includes physical model, Kinect scanner, and computer with Rhino, Kinect driver, and Quokka add-on installed. The black façade surface is the object to be scanned and re-worked in Rhino.

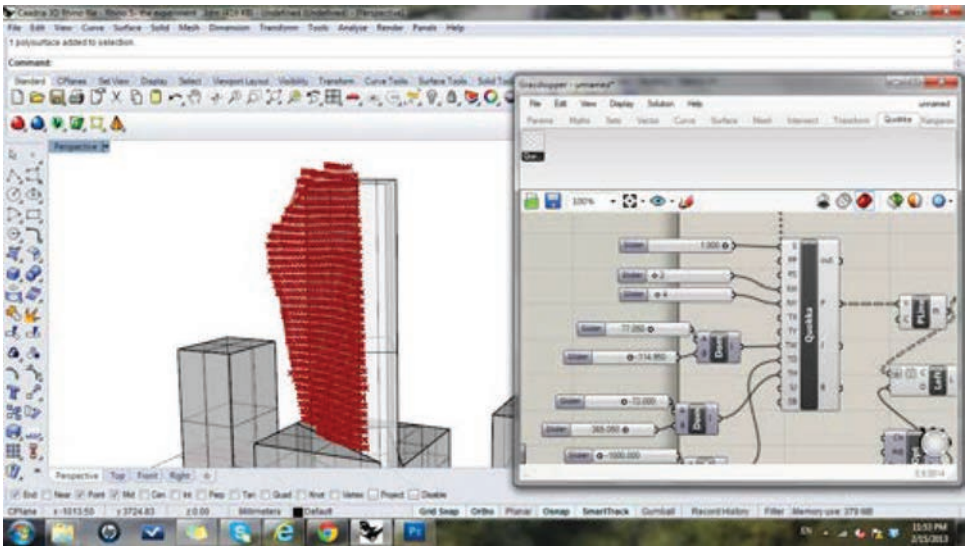

Figure 4. Screen shot of scanned model and scanned, point-cloud surface, and Grasshopper diagram.

installed (Figure 3). The physical model was first created digitally and then sent to a laser cutter and assembled manually. Once the add-on and Kinect driver were installed, the digital model was aligned with the physical model. It was scanned and the point cloud was cropped to the area the designer intends to work on in Rhino. In this case we have chosen a façade tower surface. This point cloud, (pictured in red) treated as a surface, directly corresponds to any movement or manipulations of the physical model in real-time (Figure 4).

A point cloud is a set of points that exist in three dimensions, thus every point is defined by three coordinates; X, Y, and Z. While point clouds can be used in some 3D applications, the process of reconstructing the surface can be made through converting the points into a 3D surface. However most of these processes lack a consistent method of reconstructing the surface using point clouds.

A surface can be created in Grasshopper from the selected point cloud by using Delaunay meshing, such as is used in many 3D scanning programs when reconstructing a surface. Another method of reconstructing the surface is through lofting (Figure 5). An advantage of the Grasshopper tree data structure of Quokka's depth point cloud data is that section lines of a subject surface or object can easily be generated with the Grasshopper Curve or Polyline components. These section lines can then be lofted, and the options for lofting a surface in Grasshopper can be used. The lofted surface can in this way be created as a developable surface which will enable the designer to unfold the surface as sheets that can be manufactured as components or as a whole.

Figure 5. A point cloud for a surface, section lines, and the lofted surface.

4. Beyond Reality Capture: Real-Time Generative Design

Reconstructing a surface with Quokka provides an interesting generative design method. Elements of a dynamically changing physical surface can in real-time be morphed in Grasshopper according to its specific properties (Figure 6). This is

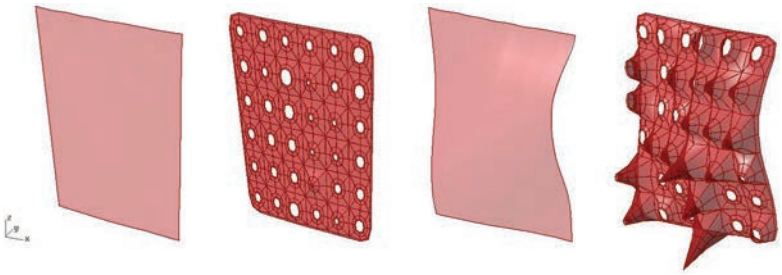

Figure 6. Reconstructed surfaces generated from Quokka, and real-time deformation of those surfaces based on surface curvature.

particularly useful when designing with curved, non-standard surfaces. A designer can create a generative dynamic model from a physical object and manipulate it in real-time to test its viability. This illustrates the importance of the real-time script to derive the best way of defining properties for freeform surfaces such as thickness and structural properties which can be tested in real-time digitally by adding structural behaviour parameters to the digital geometry.

5. Conclusion: Future Architectural Implications

The systems developed through these approaches have a number of experimental/pedagogical applications in architecture such as performance in architecture, interactive design, collaborative design, 3D scanning, real time data capture and shape design recognition, shape assessment, and feedback design.

Additional components can be developed within Quokka to manipulate the point cloud data. Such components could be developed with the Point Cloud Library (PCL) (pointclouds.org) to implement, for example, point cloud stitching for full 3D scanning of objects and object recognition.

5.1. CHEAPER, FASTER, EASIER

For less than AUD $200, an architect or student could set up the 3D scanner with his/her computer, and use a new tool which bridges the gap between working with a physical model and attempting to create different digital morphologies. Students and practitioners would not be confined to algorithmic space of computer programs in order to generate digital forms. Models can start out as physical models and be easily scanned. Once digitised it will be easier for architects to manipulate designs and complete changes and revisions. Because this method is inexpensive

and easy to use, its diffusion and adoption as a common practice by a large cohort of architects and students is possible.

A type of design 'cross-breeding' can occur, where existing known forms, for example the model of a designer car, can be scanned and reversed engineered to obtain and apply curves for the design of a building such as a car showroom.

5.2. PEDAGOGICAL IMPLICATIONS

The use of 3D scanning with Quokka addresses some of the problematic issues of generative design in academia. Scale has always been a problem among students, however it is exaggerated through the implementation of generative design processes which seem to begin in a black void of outer space. It is difficult for students to envision these shapes as habitable, *scaled* buildings within a real urban context. By starting out with a physical model that contains an urban scale, students can immediately view how their generative design fit within a scaled context and easily make modifications accordingly.

This method also eliminates the problematic decision for students as to whether they should complete their work in digital or physical model form. Users can see the outcomes of their physical models in digital form immediately, rather than having to create a physical model, scan it, alter model, etc. This process does away with the need of discriminating between working drawings and models and finished presentation drawings and models.

5.3. IMPLICATIONS FOR DESIGNING IN A DYNAMIC POINT CLOUD

This is an exciting area which we hope to see a lot more innovation in the future using 3D scanning and Quokka. Some improvements and implications of using a dynamic point cloud would be the introduction of vector motion into the design process. Non-standard curved morphologies can more easily evolve from static curved surfaces to dynamic, kinetic, and responsive facades and walls. These, in turn, can be formed from an array of shaping vectors from wind patterns to sun orientation. However it should be noted that the Kinect scanner cannot scan reflective surfaces nor can it scan in bright, sunlit conditions.

A recent version of the Quokka add-on along with installation instruction can be found at: http://quokkalab.com.

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References

Borenstein, G.: 2012, *Making Things See: 3D Vision with Kinect, Processing, Arduino, and Makerbot*, O'Reilly, Beijing.

Fitzmaurice, G. W., Ishii, H. and Buxton, W.: 1995, Bricks: Laying the Foundation for Graspable User Interfaces, *Proceedings of CHI '95*, ACM, 442–449.

Frazer, John: 1995, *An Evolutionary Architecture*, Themes VII and Architectural Association, London.

Ishii, H. and Ullmer, B.: 1997, Tangible Bits: Towards Seamless Interface Between People, Bits, and Atoms. *Proceedings of CHI '97*, March 22–27, 1–8.

Kramer, J., Burrus, N., Herrera C., D., Echtler, F. and Parker, M.: 2012, *Hacking the Kinect*, Apress, New York.

Piper, B., Ratti, C. and Ishii, H.: 2002, Illuminating Clay: A Tangible Interface with Potential GRASS Applications, *Proceedings of the Open Source GIS – GRASS User's Conference*, Trento, Italy.

Salim, F., Jaworski, P., Kaftan, M., Friedrich, E., Urquiza, R., Oh, S., Fihn, J., Galaso, J. L., Roa, R., Banke, T., Bak, J., Kalvo, R., Di Leo, S., Madeddu, D., Albuquerque, J., Gillespie, D. and Østergaard, J.: 2011, Informing Architecture and Urban Modelling with Real-world Data on 3D Tangible Interfaces and Augmented Displays, *Integration Through Computation*, Association for Computer Aided Design in Architecture (ACADIA), Alberta, Canada, 226–233.

Trossell, W. and Shaw, M.: 2011, SCANLAB, *in* R. Glynn and B. Sheil (eds.), *Fabricate: Making Digital Architecture*, Riverside Architectural, Toronto.

Webb, James and Ashley, James: 2012, *Beginning Kinect Programming with the Microsoft Kinect SDK*, Apress, New York.

Yang, W.-B., Chen, M.-B. and Yen, Y.-N.: 2011, An Application of Digital Point Cloud to Historic Architecture in Digital Archives, *Advances in Engineering Software*, **42**, 690–699.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 271–280. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

GROUP FORMING: NEGOTIATING DESIGN VIA WEB-BASED INTERACTION AND COLLABORATION

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Abstract. This research project proposed to create spatial and communal qualities of Group Form architecture via a web-based user participation design method. The proposed method allows multiple users to simultaneously design houses on the same site, encouraging spatiotemporal negotiation as users interact and collaborate with one another. In order to assess the feasibility of this approach, a prototype of a web-based Group Form design tool was implemented using the Processing environment. An experiment using the web-based tool was conducted with the objective of exploring the actual user behaviour.

Keywords. User participation; group form; web-based tool; Processing; collaborative design.

1. Introduction

Online user participation in design is becoming more prevalent in today's world. Involving users in design can lead to a better fit between design and different user needs and can result in a sense of ownership over the design outcome. The Internet has become an invaluable tool to enable such user participation as users can interact via the web from any location over extended periods of time. Furthermore multiple users could be logged in at the same time, thereby creating opportunities for user-user interactions.

Collective Form, or Group Form (Maki, 1965) architecture can be found in medieval cities and traditional vernacular communities. They typically emerged over a long period of time, from spatial negotiation between neighbours as land was urbanized and as new buildings replaced the older ones. This process can be seen as a bottom-up planning approach where a micro single house unit is the generator of the macro village form.

Many architects today find the spatial relationship inherent in Group Forms as having desirable qualities. In some cases, they attempted to create these Group Form qualities in a top down manner though following certain spatial rules. For example, in Japanese architect Koji Tsutsui's Annular Orphanage in Uganda, Africa, clusters of housing facilities are formed by positioning rectangular units at a 45 degree angles to the adjacent units (Tsutsui, 2010). However, these attempts to create Group Form are missing certain key elements of how Group Form emerges in a bottom up manner.

This research project proposed to create spatial and communal qualities of Group Form architecture via a web-based user participation tool. The research begins with a precedence study of existing web-based tools available. Various types of user-design method are brainstormed and a prototype is created based on the proposed system. Also, the concept of user-to-user interaction via the web-based tool will be developed. Finally an experiment is carried out to test the approach and the outcome will be discussed.

2. Existing Web-Based Tool

Researchers have developed a wide range of web-based tools that allow end-users to design spaces and buildings. Three recent tools that allow end-users to customise residential designs will be briefly reviewed: WIDE Kingdom, Hinterland Koeln, and Bar_Code Housing System. Table 1 below gives an overview of key features of each of these tools.

Table 1. Comparison between three precedence studies.

	Stages	**Instant Feedback**	**Direct manipulation of space**	**User-User Interaction**
WIDE Kindom (2001)	Yes	Yes	No	No
Hinterland Koeln (2010)	Yes	Yes	Yes (Façade only)	No
Bar_Code Housing (2011)	Yes	Yes (2D only)	No	No
Proposed Web-based Tool	Yes	Yes	Yes	Yes

WIDE Kingdom (Chien and Shih, 2001) allows users to customise the design of their apartment units. It employs information filtering as the key mechanism for the customization of apartment units. Users can select the apartment unit, arrange the layout, try different interior finishes, and choose furniture via drop-down lists and text-field. While the manipulation of space is limited, the outcomes are rendered realistically in 3D for visualization.

Hinterland Koeln (2010) is a tool that allows citizens to build their houses within the courtyards of existing building plots. Users can outline their building plot on the map by drawings a shape using the mouse. Various parameters, including the elevation and floor height of the building, can be adjusted via sliders and the changes are reflected simultaneously. These features make the tool very intuitive for the laymen.

Bar_Code Housing System (2011) is a building system for the construction of affordable mass housing blocks with industrialized process. A tool has been created that generates a floor plan automatically based on a set of parameters input by the user, including the number of inhabitants and programmatic requirements to have the system. The tool is accompanied by a comprehensive web environment that facilitates communication and the collaboration amongst the stakeholders involved in the building project.

All three tools allow users to create customised designs via a web-based interface by specifying selections, parameters, and forms. However, it is noted that in all three cases the interaction is solely between the user and the tool. For a design method capable of generating Group Form, a tool would be required that supports user-to-user interaction. More specifically, one of the key elements of Group Form architecture is spatiotemporal negotiation between people with multiple conflicting goals. A Group Form design method is proposed that enables users to negotiate their design decisions via online interaction and collaboration.

3. Proposed Group Form Design Method

The proposed Group Form design method focuses on residential design, and involves both architects and end users in a structured process. The method consists of three distinct stages: *schema development*, *design development*, and *detailed design*.

- In the first stage, the architects would develop a set of spatial rules, referred to as the *design schema*. These rules would be encoded into a user-friendly web-based Group Form design tool that would allow non-experts to design their own residential units.
- In the second stage, end-users would use the Group Form design tool to develop their own designs. The design possibilities would be constrained by the architect's

spatial rules embedded within the tool. Multiple users would work on their designs at the same time within a single site over a specified limited period of time. Each participant would be able to see their neighbours design emerging over time, and various mechanisms would be implemented to allow multiple conflicting design decisions to be negotiated through online interaction and collaboration.

- In the third stage, the architect would take over the final negotiated design and develop it into a detailed design proposal.

4. Prototype Group Form Design Tool

A prototype Group Form design tools has been implemented as a web application written in the Processing language (Processing, 2010). The tool uses a client-server architecture, where the server hosts all design data, and clients are used to connect to the server and edit the designs.

The user works with the client application on their local computer, and over a period of time develops their design. Each time they make any changes to their design, the modifications will be sent to the server and the central model will be updated. If multiple users are logged in at the same time, any changes made to their design will be reflected on other users screen almost instantaneously. In addition, each user will have an avatar, and will see other user's avatars walking around and designing their housing units.

In order to explore the concept of spatial negotiation, it was decided to allow users to compete with one another in defining the spatial location of their house. Thus, rather than assigning each user to a predefined plot, they were allowed to claim any part of the site as their own. Conflicts could then be resolved either through consensus or through auction-style bidding. The former method involves users communicating with one another through online messaging. The latter method involves each user placing financial bids on the area of the site in question, with the highest bid wining. In addition, a complex spatial organisation was proposed, whereby individual housing units could be built on top of each and interlock in non-standard configurations. In order to ensure that no lifts were required, the height was limited to four floors.

4.1. SPATIAL RULES

In order to implement the tool, the first step was to define a set of spatial schema rules that allow designs to vary widely in terms of their overall organisation, but that also constrain them to be viable. These rules were then embedded in an easy to use software tool that would allow non-experts to create designs for their own housing units.

Initially, a range of alternative approaches were experimented with, including *free-hand drawing*, *component assembly*, and *cell selection*. Free-hand drawing has few constraints, and allows users to draw on a canvas. Component selection presents the user with a set of components that can be assembled in various ways to 'build' the housing unit. Cell selection discretises space into a set of regular cells, and allows the user to define the volume of their housing unit by selecting cells in 3d space.

A hybrid approach was finally selected that combined cell selection with a number of other techniques. In the first step, the volume of the site was discretised into a cellular grid and users define the volume of their house by selecting a set of cells. In the second step, the wall areas are divided into a smaller cellular grid, and doors and windows are inserted by specifying their insertion points.

The cellular grid was developed through a number of iterations. In the earlier iteration, various grid sizes were experimented with. However, the same grid has to be used to define all the spaces in the housing unit, which makes it difficult to select an appropriate cell size. On the one hand, if the cell size is too large, then the design moves became too coarse, with users being forced to add unnecessarily large cells. On the other hand, if the cell size is too small, then the design moves become too fine-grained, forcing the user to painstakingly select numerous cells to define their housing unit.

After exploring various options, a specialised technique was developed that allowed users to adjust both the position and size of the inhabited room volume in the cell. The inhabited room volume was set to be smaller than the size of the cell. The cell size was set to 8 x 8 meters, while the inhabited room volume was set to 6 x 6 meters. Once the user had selected a cell, they could then offset the inhabited room volume by pushing it into any of the four cell corners. In a second step, they could further tweak the dimensions of the inhabited room volume. The original 6 x 6 meter space could be resized in steps of 0.5 meters, with a maximum of three steps. Hence, in plan the area of each inhabited room volume could vary from 25 to 36 square meters. This allowed users to easily define their housing unit by selecting a small number of cells, while at the same time allowing users to have fine-grained control over the dimensions of each inhabited room volume. Figure 1 shows the

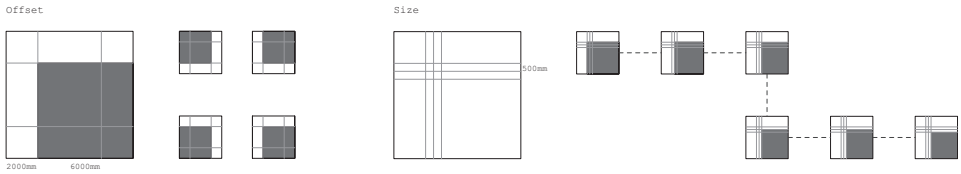

Figure 1. An inhabited room volume within a single cell offset to 4 positions (left) and changing size (right).

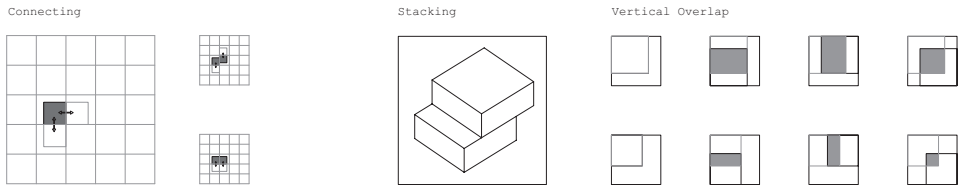

Figure 2. Connecting cells with enforced constraints.

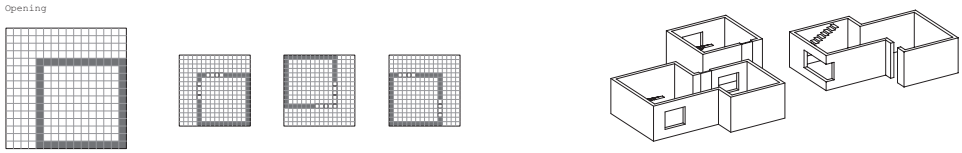

Figure 3. Adding windows.

inhabited room volume being offset within the grid cell to the four different positions and being resized to various different sizes.

In order to ensure that reasonable housing units are generated, three key of constraints are enforced: *gravity*, *connectivity* and *size*. The gravity constraint ensures that users are not able to select floating cells. They can only select cells that are positioned either on the ground or on top of other cells. The connectivity constraint ensures that users select cells that form one single connected habitable room volume. When selecting the first cell, any non-floating cell on the site can be selected. However, after that, they can only select cells adjacent to (including above and below) the already selected cells. The size constraint ensures that users cannot select beyond a certain limited number of cells. There is a maximum of four floors, and the user can select a maximum of four cells per floor.

Finally, once all the cells have been selected and the habitable room volumes defined, the user can then progress onto defining more detailed components of the design, including in particular the positions of the windows and doors. The walls are divided into square 'bricks' measuring 0.5 x 0.5 meters. Windows and doors can then be inserted into the walls by specifying the insertion point in this wall grid. Figure 3 shows the process of adding windows and doors to the walls.

In order to resolve conflicts of cell occupation, the tool allows users to compete for a cell by bidding money. Each user would offer bids for the cell and the user with the highest bid would eventually win the cell. Due to site conditions, certain areas might have higher demand such as those with better view. This approach

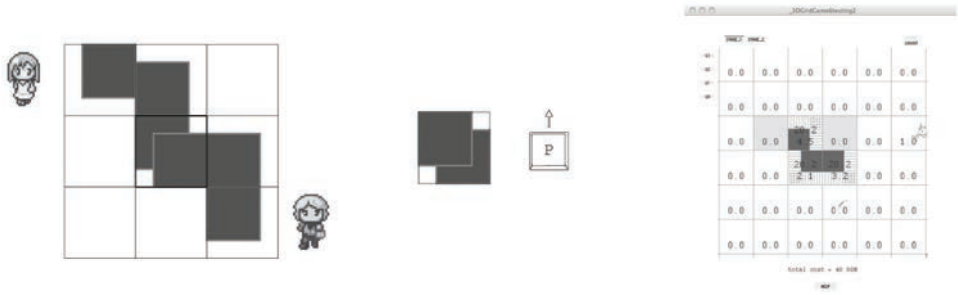

Figure 4. Resolving conflict with an auction style bidding system.

will therefore allow the financial cost of the space volume (and land) to emerge in a bottom-up manner through individual negotiations.

4.2. GROUP FORM TOOL

The final Group Form tool allows users to progress in a fluid and users-friendly manner through the two design steps of defining the habitable room volume by selecting cells, followed by inserting doors and windows.

Figure 5 shows screen shots of a user's interaction with the Group Form tool. For clarity, this scenario only contains a single user. The top three screen captures show step 1, in which grid cells are selected and habitable room volumes are defined. The bottom three screen captures show step 2, in which windows and doors are inserted.

Although an underlying grid is used, the resulting arrangement of units in plan and section do not suffer from monotony, as each user's customisation creates significant variability. Figure 6 shows an example of a plan generated using the schema rules described above.

4.3. GROUP FORM EXPERIMENT

In order to test the feasibility of the proposed Group Form design method, an experiment was conducted. The objective of the experiment is to explore actual user behaviour when using the tool as the feedback is invaluable for further improvement and implementation. The experiment was held in School of Design and Environment, National University of Singapore's computer lab.

Ten architecture students from fourth and fifth year participated. Participants were each given a character card with a role they had to assume. On the card, basic information such as name, age, gender, budget and occupation was stated. Some

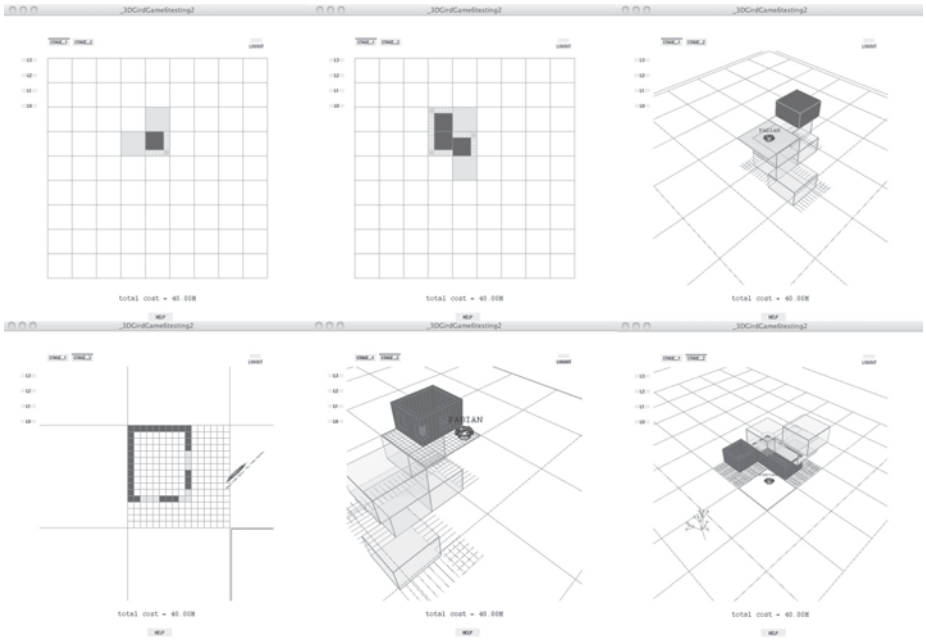

Figure 5. Screen captures of a single user working with the Group Form tool.

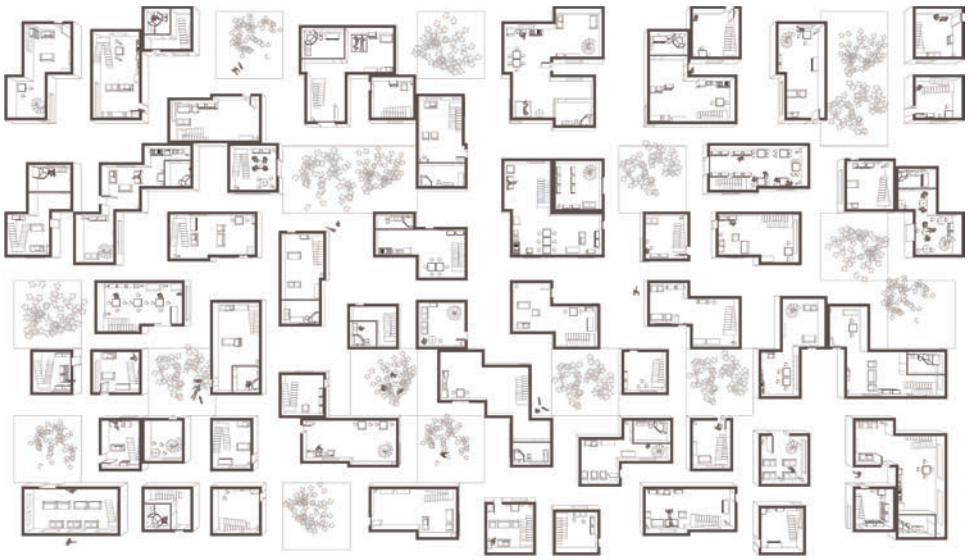

Figure 6. Floor plan generated using the spatial rules.

characters were related. In addition, some of the families were related to each other and therefore included preferences to live closer together. Participants were encouraged to consider the site condition (a square plot of land with forest, river, carpark or road on each side), the number of rooms required, their budget and land cost.

The experiment lasted for 40 minutes. After the experiment was complete, participants were asked to write down their aims, whether they have achieved their aims, and if they are satisfied with the outcome. They were then asked for more general feedback on the Group Form tool and how the prototype could be improved.

4.4. EXPERIMENT OUTCOME

The experiment resulted in a complex and spatially rich outcome. Users successfully developed designs for housing units that performed reasonably well from a functional point of view. From the point of view of developing a Group Form, the process of online interaction and collaboration was varied, and differed significantly from one user to the next. However, in general the feedback was positive as users could see the potential of such as design approach.

Based on the experiment, three key weaknesses were identified. First, better tools are required for user-to-user communication, such as support for private and group discussions and for the ability to annotate objects in space with comments. In addition, the resolution of conflicts through auction-style bidding required refinement.

Second, additional constraints can be added to disallow design moves that are clearly not desirable. For example, constraints could be added to disallow one user to place a window directly opposite and other users window, thereby avoiding privacy problems.

Third, additional feedback can be added. For example, in the current system, feedback on the land cost and construction cost are continuously display to the

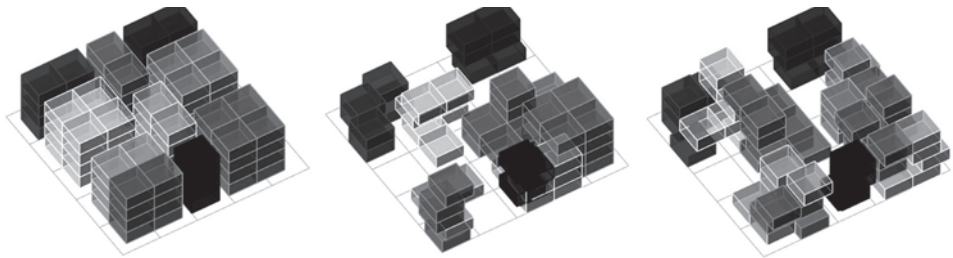

Figure 7. From left to right: Worst-case outcome, experiment outcome, expected outcome.

user. As these users are not expert designers, additional feedback such as predicted energy consumption and daylight levels could help improve the designs that are generated.

5. Conclusion

This research proposed a web-based design method for developing Group Form that supports spatiotemporal negotiation through online interaction and collaboration.

The method consists of three stages: in the first stage, architects encode a set of spatial rules within a design tool; in the second stage, non-expert end users use the tools to design their individual housing units; and in the final third stage, architects take over the negotiated design and develop it further into a detailed design proposal.

In order to demonstrate the feasibility of this method, a prototype of the web-based Group Form tool was implemented. This tool allowed users to design individual housing units within a shared virtual site, with real time feedback. The experiment highlighted the potential of the proposed method.

References

Maki, F.: 1965, Some thoughts on collective form, *in* G. Kepes (ed.), *Structure in art and in science*, George Braziller, 116–127.

Tsutsui, K.: 2010, 11 Koji Tsutsui, *JA: The Japan Architect*, **77**, 102.

Chien, S.-F.. and Shih, S.-G.: 2001, Design through Information Filtering, *in* B. de Vries, J. van Leeuwen and H. Achten (eds.), *Computer Aided Architectural Design Futures 2001*, Springer, 103–110.

"Hinterland Köln": 2010. Available from: Youtube <http://www.youtube.com/watch?v=ZAfw5HSzJto> (accessed 10 December 2010).

"Bar_Code Housing System"; 2011. Available from: Bar_Code Housing System <http://www.barcodehousing.net/> (accessed 1 February 2011).

"Processing": 2010. Available from: Processing <http://processing.org/> (accessed 20 October 2010).

"Group Forming": 2011. Available from: Vimeo <http://vimeo.com/26638743> (accessed 7 December 2011).

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 281–290. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

AMONG WAYS OF LIVING

Looking at diversity from cultural actions and digital media

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Abstract. This paper presents reflections stemmed from a research that seeks to cast a gaze toward the diversity of ways of living in communities, starting from the interaction in communicational processes structured by digital means. This paper introduces findings on the possibilities of similarities between people of different groups in a community in hybrid instances, starting from cultural activities. Further explorations about the potential and qualifications of the use of digital media for this purpose will also be presented. The trials that comprise the object of reflection in this article took place and were only achievable for being part of a larger public policy project, funded by an important Brazilian research funding agency. The project has been in development since March 2010 by the research group of a recognized leading university and involves post-doctoral, doctoral and master researchers. Additionally, the project has partnership with various third sector institutions such as NGOs and collectives, as well as music bands and European universities.

Keywords. Diversity; ways of living; digital media; communities; communication.

1. Introduction

In this paper we present considerations derived from experiences within a research developed during three years and that was aimed at learning and verifying the diversity of ways of living in communities belonging to different social and urban realities using for this digital media, starting from communicational processes, in the ambit of cultural actions occurred within a large public policies project.

Encouraged by previous successful experiences in this research area, the group Nomads.usp, Center for Interactive Living Studies, acknowledged the important need to search for methodological procedures and practices in qualitative research which would comprise more embracing aspects and that would enable to bring the

researcher closer to the studied reality. In addition to this, the verification and use of digital media potentialities for such procedures, starting from a low-tech structure of easy reproducibility, as it has already been the premise adopted in researches conducted at Nomads.usp for over ten years.

The project in question is called "Hybrid Territories communities, cultural actions and digital media" and it belongs today to public policies funding line at FAPESP[1], and it has been in development since March 2010 by Nomads.usp[2], at University of Sao Paulo, Brazil. Master, PhD and post-doc researches are involved turning discussions the result of a large process developed by many researchers working and reflecting together. Furthermore, the project is structured by partnerships with the tertiary sector such as collectives, NGOs, partnership with music bands and artists with local public bodies linked to cultural production and promotion as well as Brazilian and European universities.

In Brazilian socio-cultural reality and context, the funding and the development of this line of projects represents a considerable advancement in terms of expanding and bringing to surface innovative practices with a less centralized decision power and with other attitudes in regards to the promotion of public social well-being.

Cultural actions developed by the project and presented in this paper will be made available – as a step-by-step – to public institutions, collectives and regular people at communities looking at implementing similar practices, liable to be adapted and re-used.

2. Ways of Life, Diversity and Communities: Some Theoretical Explorations

The interest for understanding and perceiving different ways of life is identified as a way for architects and researchers, also from other knowledge areas, to cast a closer glance on realities outside the academic circle, in order to perceive and think about the importance of this approximation in a more empirical way.

The notion of community, in the context of this research, is close, among others, to that of Stuart Hall (2003, p. 66) who defends that, for the most part, these heterogeneous groups of people, originating from different cultural contexts, bring also together different origins and cultural heritage and configure a rich and plural whole, influences present as references to "communitarian self-definitions", that although they are present, remain in a constant revision, merging and relativization process and not as a static and unchangeable understanding, a social formation that is constituted starting from the difference, by a "variety of articulations, ideas and social practices" (Hall, 2003, p. 52).

The notion of ways of life as practices present in the everyday life of individuals belonging to a specific community is related to its point of views, according to Raymond Williams (1961, p. 55; quoted in Hall, 1980, p. 59).

> "Since our way of seeing things is literally our way of living, the process of communication is in fact the process of community: the sharing of common meanings, and thence common activities and purposes; the offering, reception and comparison of new meanings, leading to tensions and achievements of growth and change".

3. Communicational Processes and the Role of Digital Media in Respect to the Goals and Practices Accomplished

The idea that ways of life are a reflex of the way people understand themselves and share this understanding with each other, is imbricated in the communicational processes that make this exchange possible. For this work, they are not constituted as an investigative concern per se, but rather in what this process, when conducted by starting from different supports (messages, digital graffiti, music, etc.).

The exchange processes involved in the communication of groups of people involves other possibilities such as:

> "[…] access into what was opaque, knowledge where there was previously ignorance, bringing close what had been remote – all these capabilities of pervasive computing transform our ideas about space." (Cuff, 2003, p.45).

Castells has extensively developed, throughout his work, reflections of different orders on the power of different forms of sociability and communicational networks, changes in the way we communicate and pointed to a new structure in force that is controlled by the flux and intensity of information in transit (Castells, 1999). In his work Communication Power (Castells, 2009, p. 10), the author defines this power as "the relational capacity that enables a social actor to influence asymmetrically the decisions of other social actor(s)". He also argues that he understands this question as not exactly a prerogative of a specific group of people but rather as a form of relationship among individuals. It is through the possibility of new forms of communication in communities geographically distant that people of a specific group are able to share points of view and knowledge, in virtual instances. The communicational processes observed are constituted as a medium to the agency of points of view and the articulation of their differences.

4. Communities and the Actions Accomplished

4.1. TIRANDENTES CITY AND CDHU

The activities presented in this work have been carried out in two different realities and localities (Figure 1). One in a district in the outskirts in the east region of São Paulo, the district of Tiradentes City, the largest complex of public housing estates in Latin America, located approximately 40 km from downtown São Paulo;

Figure 1. The district of Tiradentes City and CDHU, respectively (Nomads.usp, 2012).

the other locality is in the outskirts of the city of São Carlos, – which is located approximately 230 km from São Paulo – in the district of Vila Isabel, the public housing estate Waldomiro Lobbe Sobrinho – known as CDHU – with an estimated population of 4.000 inhabitants (São Carlos total population is approximately 220.000 inhabitants).

If on one hand the Tiradentes City in São Paulo presents a formal population of 200.000 inhabitants, with an estimated 70.000 "informal" population; on the other hand, the São Carlos area presents a population of 900 inhabitants. Both areas consist of groups of vertical housing estates or tower blocks with unities of a same project built by the Public Authority.

After previous experiences based on qualitative methods such as semi-structured interviews and after some initial contacts with residents of housing estates involved in the research, we came to the understanding that the Hybrid Territories project demanded and offered the possibility of experimentation of not so usual methods that are more efficient for the understanding of the diversity of ways of life in the communities in question but also attentive to pre-existing practices that are already accepted by those communities.

4.2. STREET RADIO

4.2.1. Process and realization of Street Radio

The Street Radio, as its creators the actors at the Instituto Pombas Urbanas (Urban Pigeons Institute) call it, consists in an ornamented mobile tricycle equipped with a

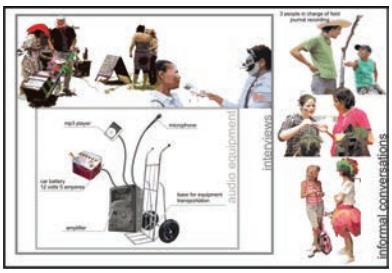

Figure 2. Street Radio Diagram (Marqueto, 2012).

sound system connected to a car battery and incorporated to its structure. Its visual appeal is aimed at drawing the attention of passers-by to the intended message. It was used for years by the actors of Instituto Pombas Urbanas as a communication channel for events promoted by this cultural center. For the purposes of our research we use this device as a way to dialogue and to listen to local residents, to perceive different postures and to report on the reality of the place and on how it is living in it, facilitated by an informal atmosphere created by the presence of the Street Radio, by disguised actors and researchers and by the sound equipment (Figure 2).

The Street Radio was conducted in the Tiradentes City streets and it was equipped by the sound system. Interviews were conducted with the Radio itself and the researchers surrounding it were also conducting informal conversations with people around the event and who many times provided quite deep reports on everyday life issues. Researchers posed questions on how it was living in Cidade Tiradentes and about their point of view on how it would be to live in a housing estate with identical housing units but in São Carlos, in this case at the CDHU. The reverse was made later at the CDHU (Figure 3).

Despite the existence of a central question we were also interested in the emergence of other issues and aspects of everyday life. The record was made by video footage with the aim of propitiate a second reflection moment by community residents together with researchers.

Street Radio was able to generate an informal atmosphere in the surroundings of the path traversed by it. The Radio created an ambience appropriate for interaction among children, youth, adults and elderly people in the streets and squares through which it passed.

Whilst in movement it was perceived in the Street Radio structure the formation of interaction spheres of performers and researchers with community residents: interviews by radio, informal conversations and records for future discussions.

Interviews with loudspeakers contemplated briefer answers but that did not appear to intimidate, on the contrary, it was as a dialogue with the community

Figure 3. Street Radio at Tiradentes City (Nomads.usp, 2011).

itself was established. Generally speaking, aspects of everyday life in the community were approached such as the issue of drug addiction both by teenagers and children, the transformation experienced by the housing estate in the last ten years, the living in community as a way of sharing experiences, the construction of cooperation ties between residents, celebrations and events occurred, the coexistence of different everyday practices, violence, the presence of narcotics dealing, the presence of the Instituto Pombas Urbanas as a cultural agent and social transformer as well as idealizations regarding life in another housing estate but in a smaller city.

At the same time, informal conversations surrounding Street Radio originated from issues announced on loudspeakers but entered other spheres of depth and resulted in quite personal reports, for instance, from mothers who suffered from having sons involved in dealing or using narcotics. Or also reports on how important it was to live in a community where everybody know and help each other and the wish that future generations could continue living there. These reports have been recorded also in a field diary by researchers who described in details conversations and experiences in field.

4.2. CDHU CULTURA FEST

Another cultural action to be approached is called CDHU Cultura Fest and it took place at the CDHU in the city of São Carlos. The event realization was also understood as a methodological procedure to understand ways of life and the coexistence of differences, able to bring us another gaze on the same community. As a large event that sought to reunite different groups within the community, there have been diverse activities available and among these we will deal with

these: digital graffiti; screening of comments during the event; street dance and music band playing remotely.

4.2.1. Screening of comments

For the screening of comments researchers circulated during the event with notebooks, talking to residents and inviting them to give their opinions through a comment that would remain stored in the Hybrid Territories project website (Figure 4).

We could perceive the reclaim of a promotion of moments that could propitiate the contact with different forms of culture; the issues of drugs and violence were also present. As in the Street Radio, we could perceive, in informal conversations, the reverberation of what was being screened. These conversations also showed where, in the opinion of many of the people concerned, cultural practices and events were located as well of showing how they saw that possibility of coexistence of groups that don't usually talked to each other within the community.

Figure 4. Screening of comments at CDHU Cultura Fest (Nomads.usp, 2012).

4.2.2. Digital Graffiti at the CDHU Cultura Fest

This procedure was conducted through open source software, in this case laser tag, and low cost, in this case touch tag, which were also previously tested by graffiti artists resident at the CDHU.

For Laser tag we used a notebook with software developed by the Research Lab installed and linked to a projector, a long-reach laser and a recording camera linked to a notebook, capturing the laser movements. For the Touch tag we used a tablet with the installed software connected to a projector (Figure 5).

During the event both structures were made available for public use so that it could be used as a form of expression and language not necessarily verbal.

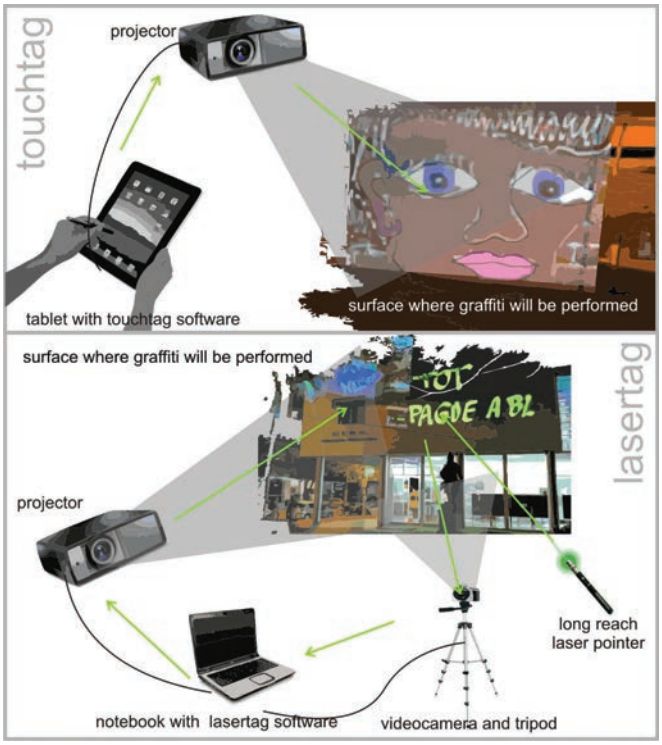

Figure 5. Digital Graffiti Diagram (Marqueto, 2012).

The procedure attracted mainly children and youth who marked with drawings things from their everyday life such as tags and words that mentioned musical styles or slang while children elaborated drawings stemming from the imaginary of housing or nature.

4.2.3. Street Dance and bands playing remotely

This consisted of a presentation of a street dance group and two bands playing simultaneously, one located in the city downtown, in a studio, and the other in the event location. The bands could experience the musical production remotely by using skype software (Figure 6).

Both presentations brought in their musical themes issues related to life in the outskirts in general. In this moment a large public was attracted, an interesting moment of intense reunion of people from different postures, age and groups within the community: from conservative ladies to youth, adults and children.

Figure 6. Street Dance and bands at CDHU Cultura Fest (Nomads.usp, 2012).

This form of expression through dance and music may have caused a possible recognition with the population and may have drawn its attention. The fact that two musical bands played remotely, of course, brought numerous interesting questions to the research. However, we have not perceived clearly that this factor caused a strong attraction on CDHU residents.

5. Final Considerations

At the end of the presented experiences it is possible to perceive the experience of a potential still in development of the tested mechanisms. Even if it was possible to learn about the existence and about some aspects of different ways of life in the researched communities, a very large material, and recorded in the research group database, it was possible to come to conclusions that orient some forms of gazing, that verify the use of digital media in specific practices and that point to possible future explorations.

The experiences were configured by moments in which planning was successfully accomplished and other in which it needed revisions and this fact turned out to be positive for the research as it allowed us to understand that in this area of investigation there are no formulas and that we need to be attentive in relation to the demands that arise in field, from the public, directing the research steps in a positive way.

It was interesting to note the residents' different receptivity in relation to semi-structured interviews and Radio Street interviews. There was a considerable change in the residents' predisposition to express themselves in relation to everyday life in the housing estate and this reflected deeply in the quantity and in the quality of the information gathered. In other words, we are under the impression that, through a more fun approach the population felt more motivated to talk and

to express an opinion on how it is to live in this estate and it was not only impelled to answer questions posed by interviewers.

Again, a less traditional approach regarding the information gathering has proved to be less intimidating for the population and this resulted in more willingness and motivation on behalf of the population to express itself in a natural and spontaneous way.

We sought to present procedures that could assist in understanding this diversity within a community, incorporating to the process the use of digital media as interaction-promoting agents, exploring its potentialities so that they can also provide a revision of the uses given to urban space, possibilities of requalification by the social interaction of a community that appropriates this space by cultural expression. Such process is understood as a system liable to additions and other appropriations as well as being applicable, given its transdisciplinary character, to other areas of knowledge. We also acknowledge the possibility of guiding architects and researchers to merge and relativize points of view on communities, on urban realities and on the use of procedures to understand them and incorporate them to academic and professional practices.

Procedures developed by the research have also adjusted themselves as a form of empowering these communities and the people that live in it as they consist in simple and accessible technological structures that can be appropriated and adapted to new uses leading to the emergence of new sociabilities and new practices.

Endnotes

1. The Project of public policies “Hybrid Territories: digital media, communities ans cultural actions” is funded by the Fundação de Amparo à Pesquisa do Estado de São Paulo - FAPESP.
2. http://www.nomads.usp.br

References

Castells, M.: 1999, *A Sociedade em Rede*, A Era da Informação: economia, sociedade e cultura, vol. 1, Paz e Terra, São Paulo.

Castells, M.: 2009, *Communication Power*, Oxford University, Oxford, UK.

Cuff, D.: 2003, Immanent Domain: Pervasive Computing and the Public Realm, *Journal of Architectural Education*, **57**(1), 43-49.

Hall, S.: 1980, Cultural Studies: two paradigms, Media, *Culture and Society*, **2**, 57–72.

Hall, S.: 2003, *Da Diáspora: Identidades e Mediações Culturais*, Editora UFMG, Belo Horizonte.

Williams, R.: 1961, *The Long Revolution*, Chatto and Windus.

DESIGN EDUCATION

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THE LEGACY OF THE HOCHSCHULE FÜR GESTALTUNG OF ULM FOR COMPUTATIONAL DESIGN RESEARCH IN ARCHITECTURE

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Abstract. Nowadays the use of computational design processes in architecture is a common practice which is currently recovering a set of theories connected to computer science that were developed in the 60s and 70s. Such pioneering explorations were marked by an interest in employing scientific principles and methodologies many developed in Research Centres located in the US and the UK. Looking into this period, this paper investigates the relevance of the German design school of the Hochschule für Gestaltung (HfG) Ulm to the birth of computation in architecture. Even thought there were no computers in the school. It is argued that the innovative pedagogies and some distinct professors have launched clear foundations that can be understood as being at the basis of further computational approaches in architecture. By describing and relating the singular work by Tomas Maldonado (educational project), Max Bense (information aesthetics) and Horst Rittel (scientific methods), this paper describes the emergence of analogical ways of computational design thinking. This analysis ultimately wishes to contribute for inscribing the HfG Ulm at the cultural and technological mapping of computation in architecture.

Keywords. HfG – Hochschule für Gestaltung Ulm; design methods; scientific methodology; information aesthetics; computational design, architecture.

1. Introduction

Albert Einstein was born on March 14, 1879 in Ulm and decades later the city would remember this by associate the motto *Ulmenses sun mathematici* (people of Ulm are mathematical) to his famous countryman. Is it just a coincidence that one of the most fundamental schools of the XXth Century, The Hochschule für Gestaltung was founded in Ulm. During its existence (1953–1968) it had three directors, the Swiss architect Max Bill (who had been on of Hannes Meyer´s students at the Bauhaus), the Argentianina painter Tomas Maldonado and the German philosopher Max Bense.

By the mid 60s, the computer was only accessible to a few mathematicians and scientists, however it became object of a much wider theorization and influence. The mathematical logic inherent to the computer supported the emergence of new scientific areas including, Information Theory, Operation Research, which caused a great impact in the domain of the Social Sciences and the Arts. Some research centers pursuing investigation upon the advances of computing technology when applied to architecture and planning started by then their work. In the UK the Land Use and Built Form Studies Center (LUBFS) at the University of Cambridge and the Design Methods Movement at the Royal College of Art in London were the most prominent. In the USA, the Architecture Machine Group at MIT and the Design Research Center (DRC) at Carnegie Mellon University begin as well to address the use of computational methods in the design process (Rocha, 2004).

However earlier this motivation was also predominant at the Hochschule für Gestaltung Ulm (HfG Ulm), in Germany. Despite its short existence, it was considered one of the most important schools in the twentieth century. The HfG had no access to computer systems and was nevertheless of extreme importance in the history of the beginning of the computer era in architecture due to the work carried out by some of its faculty members. Their research led the foundations for a new theoretical approach in architecture and design: One that uses computer science not as a tool for geometric design but as a tool for computer design. On this realm Kenneth Frampton used to mentioned that computational thinking initially characterized by an analytic approach to methods design research, or data processing that characterizes HfG of Ulm and made it famous, opened the way in mid 60`s to heuristic proceedings related to the power of new computational methods.

This particular pedagogy, constituted a legacy of computational thought, which would characterize some of the vanguard architecture in the 60s and 70s. In short, this paper highlights the contribution of the HfG Ulm, to the introduction of computation in the architecture, a history yet not much studied and known nowadays.

2. The HfG Ulm – Educational Project

The Hochschule für Gestaltung Ulm in Germany (Figure 1), founded in 1953, operated until 1968, lasted the transition from industrial society to post-industrial society. Despite its short existence during the Post-World War II period, the HfG Ulm project also rethought the role of social sciences based on a strong belief in reason. Belonging to an era of Nazi resistance, the founder promoted the idea that, in a democratic society, "good design" should be accessible to all. In one of the few critical texts regarding the contribution of the HFG, Kenneth Frampton (1974) says: "*There is little doubt that HfG has been the most significant school of design to come into existence since the end of WWII, not so much for what it achieved in terms of actual production, nor for the large number of designers it effectively educated, but finally for the extraordinary high level of critical consciousness that it managed to sustain in its daily work (...) The questions that the Hochschule began to ask a decade ago are now being asked, consciously or unconsciously, by every design and architecture school, and the crisis of identity that befell the Hochschule has now become a universal malaise*."

Teaching at the HfG of Ulm, based on standardization and mass production, investigates a scientific approach integrating systemic and objective methods of collecting and processing data in order to inform of the design solution.

It would synthesize science and design in a new scientific humanism that recognized the pluralism of methods and methodological perspectives needed by the

Figure 1. Hochschule für Gestaltung (HfG) Ulm / Ulm School of Design (1953-1968). Architect: Max Bill. Date: 1955. Source: Sammlung René Spitz.

designer in addressing the new problems of industrial culture. What did emerge however were the beginnings of an operational view of design science – what Maldonado sometimes called a "scientific operationalism"- drawing on particular methods from many disciplines, gathered in an eclectic array. Nowhere was this question more focused among designers of "Utter devastation" yet with "unlimited curiosity" about all of the new disciplines of science and new ideas in the philosophy of science and mathematics (Buchanan, 2009, p. 427). As Maldonado states, "The mainspring of all of our curiosity, our reading, and our theoretical work was our determination to find a solid methodological basis for the work of design" (Maldonado, 1991, p. 222). In this way scientific knowledge and new methods could be applied in the search of design problems solution within an industrialized environment.

3. *Computational* Approach

This paper identifies three most visible conditions that gained relevance at the HfG of Ulm: Theory, the Education Project (Tomas Maldonado); Philosophy, the Information Aesthetics (Max Bense); and Methodology, the Scientific Methodology (Horst Rittel).

3.1. THEORY, THE EDUCATION PROJECT

The ideology that emphasized the artistic dimension, a legacy of the Bauhaus carried out by Max Bill – the first director of HfG – was opposed by a multidisciplinary scientific approach, supported by the next director Tomás Maldonado. In this second phase, different subjects such as economics, sociology or mathematics, operational research, statistics, set theory, linear programming techniques, cybernetics or subjects dealing with the history of science and the theory of machines, built a dynamic that determined the emergence of this new School project. Maldonado also introduced semiotics in the curriculum, and he says: "*Our interest, especially mine, was realizing what was happening in the world of information and communication. The first thing that caught our attention and struck me over the years was cybernetics. Today no one longer speaks about cybernetics. There is a talk about communication, but no longer about cybernetics. At the time it was cybernetics of Norbert Wiener, and cybernetics, began to occupy ourselves, from global cyber which was a system of disciplines, according to the conception of Norbert Wiener, in which he had the information and especially the theory of information and of Claude Shannon*."[1]

The analytical approach with which the Ulm school became identified with gave way in the mid 60s to heuristic procedures related to the increasingly seductive

power of the computer. It is important however to highlight some background that nurtured the philosophic epistemology of the Ulm school. By one hand it was grounded in the legacy of Positivism, very much embodied in the work of the Austrian philosopher Rudolf Carnap (1891–1970) who studied physics at the University of Berlin, 1917–18, where Albert Einstein was a newly appointed professor. On the other hand was rooted in the need of new industrial needs and the early philosophy of Charles Pierce regarding Semiotics.

In 1956 Max Bense had already "paved the way" for the introduction in classes of Semiotics and of publications about the theory of signs, largely in the service of aesthetic information and focusing on Charles Pierce's categories of **aesthetics and ethics**. Semiotics was Maldonado's effort to put his "scientific operationalism" at the front of design, partly in opposition to the view of Max Bill, of the designer as a kind of aesthetic coordinator of cultural artefacts, and the school of Ulm was the first school of design to recognize this (Krippendorff, 2006, p. 305).

With his contribution to Semiotics in 1961, Maldonado published the definitions of 94 terms "Terminology Semiotics" (Maldonado, 1959). These definitions were intended to be a series of analytical tools, enhancing the semiotic discourse for design. Subsequently Maldonado's students added rhetorical concepts and applied them widely to the visual phenomenon, materializing the idealized Educational Project for the HfG, Ulm. Maldonado recalls in an interview specifically conducted for this investigation: "*My contribution was important due the formative disciplines such as cybernetics, information theory. The computer was emerging, but there was no computer at that time. We did not know the computer right now. (…) In the first year, students were linked to fundamental course in elementary school, where I think the important question and contribution was how to fix and change the fundamental course at the Bauhaus to one that assimilated these new concerns (…) In the elementary course something very interesting happened. All exercises that were made had a very special character. But apparently they had some things still related with the Bauhaus, but they included one more thing. That was the idea of how through the behaviour of elements could one create an image. The model was a grid of little dots with different diameters to produce an image. This very elementary idea allowed us to manually simulate what you would be able to do later with computers. The students were asked to make such images with incredible detail, which was an immense difficulty. Here one can see clearly the intuition of what would become a computer use, but in our case it was a manual production... that was crazy.*"[1]

3.2. THE THEORY OF INFORMATION

One of the leading figures that stood out the most in the domain of information theory and aesthetics was Max Bense, among others like Abraham Moles, a

German scholar, Physicist and Philosopher, who made Claude Shannon's theory of information popular in Germany. Claiming that the aesthetic of information must be conceived as an exact and experimental science, Bense broke up radically with the still dominant aesthetics in Germany, which had its roots in the Romanticism.

Max Bense took this issue further, regarding "information" not as an obstacle to reach beauty but, on the contrary, as a motto for a particular aesthetics, which defended the general calculability of all objects. Bense had a remarkable role in the Hochschule für Gestaltung Ulm, by inspiring the integration of scientific methods into the design process. It was also Bense who popularized Shannon's information and communication theory, and bound it together with questions of aesthetics. Bense presented a version of the mathematical theory of communication (Shannon and Weaver, 1949), called information theory, in classes between 1954–58. His Informationsästhetik (Information Aesthetics), written in 1956, used models of communication techniques to dissolve aesthetic categories into aesthetic processes. Backed by the general hypothesis of calculability of all objects, Bense`s concept was based on the formalization of aesthetic processes. Every artistic expression and each piece of art was seen as a system of signs, and a message. In the point of view of Bense, the production and reception of art according to traditional criteria of proportion, harmony and symmetry, becomes obsolete. Bense's work, thus, focused on stochastic analysis and synthesis of structures in discourse and the arts, and how they arise.

Above and beyond this analysis, he conceptualized every creative and perceptive act as the realization of a communicative act between a sender (a masterpiece) and a receiver (the observer of the art). Thus, Bense played an important role as a pioneer of the use of information theory. Research on the development of the information aesthetic also shows how a theory that underlies the aesthetic values primarily based on rational and quantifiable criteria can quickly push up against the methodological limits. Despite these limitations, the information aesthetics of Bense points three changes that still affect discussions of art and architectural production today: (1) displacement of the function of the author's art and architecture and the concept of art and architecture, such as, (2) the concept of subject and object, and (3) the role of the reception of art and architecture (Rocker, 2010, p. xxii).

A new situation arose when the first steps were taken to institutionalize the information aesthetics. Bense, who was the responsible for the department of information and theory, developed the pedagogy concerned with implementing quantitative analysis and objective methods in design. The focus became increasingly strong in design methodologies influenced by information theory, cybernetics, operations research and mathematics.

3.3. THE SCIENTIFIC METHODOLOGY

At the HfG the curriculum was academically demanding, included several disciplines related to design, including physiology of perception, ergonomics, social psychology, sociology, economics, political science, cultural anthropology, semiotics, information and theory of communication, but also traditional themes of physical and cultural history of art. They were all made relevant to design, and the intellectual framework intended to assure their integration was the philosophy of science, originally taught by Bense.

The first assignment of Horst Rittel was a lecture on information and communication theory, which everyone at that time thought to be the key to the future. Klaus Krippendorff who graduated from HfG in 1967, recalls: "*The philosophy of science became increasingly relevant to design. It turned into a systematic exploration of the heuristics that designers were using*" (Krippendorf, 2006, p. 311). Horst Rittel's mathematical training gave him access to models, theories, and conceptual frameworks that ordinary designers had barely heard of. He introduced methods of operations research, mathematical decision theory, game theory, systems analysis, and planning techniques, and thus enriched the repertoire of design supporting methods. Figure 2 illustrates Rittel's teaching Notebook where notions of logic are explained. Under the influence of Rittel, the conception shifted to a designer who would be able to handle heuristic planning and design methods, and work as equals in product or strategy development teams (Figure 2).

According to Krippendorff, Rittel greatly contributed to implement a more scientific curriculum at the school, by relating science and design, and by putting into practice the ideology of Tomas Maldonado, and the theory of Max Bense. With a background in mathematics, physics, and sociology, Rittel introduces students and colleagues to a somewhat different perspective through teaching in methodology, theory of science, and operations research. Rittel was not a taxonomist who categorized the world or a positivist, but a pragmatist in the tradition of Pierce. Full of forceful ideas, Rittel teaching methods were thought to prepare students to design a more complex world, opening possibilities for empirical investigation (Krippendorf, 2006, p. 312). Indeed, he explains that the genesis of his own approach to design methodology came when he tried, around 1960, to apply the new methods of design in the area of planning and found that they did yield satisfactory results. This led him to reconsider the foundations of design methodology (Buchanan, 2009, p. 428).

Rittel's work emphasized the early phase of planning and preparation for design work, based on operations research, systems thinking, and the use of information's to support decision – making when dealing with complex problems. However this also involved significant emphasis on human participation in the social process of decision making within organizations. It was this latter aspect of

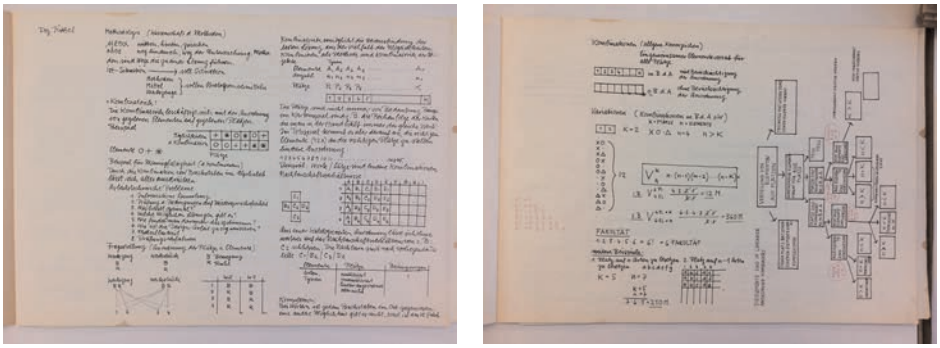

Figure 2. Discipline "Methodology" 1959, Professor Horst Rittel. Source: Archive HfG Ulm, personal photography, March 2012.

design, the human perspective and social process, which gradually emerged to distinguish his approach to design and design methodology from the others.

4. Computing without Computers

In "Looking Back at Ulm," Tomás Maldonado also stated that Ulm had a pioneering vision on the design process, but they lacked a machine – the computer. He says, "But in the midst of our limitless faith in method (…) there lay some powerful intuitions that the evolution of information technology, specially since 1963, has to a large extent confirmed" (Maldonado, 1991).[2]

Even before there were computers in HfG, a kind of "computing without computers" occurred, and this aspect was incorporated into the work of three protagonists analyzed above (Figure 3). The few who had access to computer systems at universities and companies in the 1960s shared their knowledge in literature and lectures, invited by Tomas Maldonado. So through these exhibitions and interferences, computer technology has also found its way in the HfG. However the implicit impact of new computer technology exerted by the diffusion of their general concepts rather than your hardware is not yet fully recognized.

"Computing without computers" as much as "computing with computers" led to an increased use of models and simulations in architecture. This development was, at first, a transfer from the sciences and other engineering disciplines into architecture. It was architecture's predisposition towards model making, which explains why at places like the Hochschule für Gestaltung in Ulm, information theoretical and cybernetic models were, despite their abstractness, so well received. Computing without computers allowed for the conceptualization of the computer, while computing with computers transposed the traditional modes of

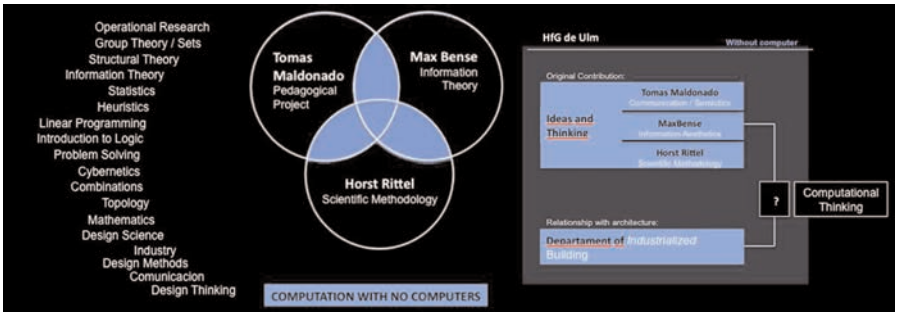

Figure 3. Synthetic scheme that relates "computing without computers" with disciplines, areas and teachers analyzed in this paper (image by the author).

operation and thinking into a new medium. It was computing without computers, analyzed in this paper through the School of Ulm, that had led to a radical shift in the understanding of subject and object that had led to a radical rethinking of the production of form (Rocker, 2010, p. xxvii).

5. Conclusion

The teaching of HfG Ulm promoted a different approach to the design process. Instead of focusing on the design and development of specific and finite forms, students sought to exploit the definition of geometric design rules to control the generation of form(s). Thus, by reflecting a scientific methodology, the design practice starts to embrace the concept of systems, where sets of interdependent information are structured to control the generation of design solutions. The exercises about geometric patterns are some clear examples where this system-based approach is evident. In them, one can see how students think about a set of variation rules for a given geometric module and, from then, conceive geometric patterns where the module is no more a fixed and repetitive entity but, instead, is an element that varies geometrically in each instance. Although these constructions are hand drawn, they already reflect a mode of computational design thinking, similar to the parametric design approaches of contemporary architecture. Expanding the manual possibilities, the computer can extend the idea of design systems to a greater level of flexibility and complexity. On the one hand, by digitally programming the rule-based design system, the designer can generate, view, evaluate and change his ideas in real time and thus refine the quality the solutions. On the other hand, the calculation power of the computer allows handling more complex design algorithms, which would be very difficult to be conceived and implemented only by mental and manual design processes.

To conclude, the HfG of Ulm pioneered in the mid 60s heuristic procedures related to the power of the new computational era. It's a scientific approach based on methods of design research on information processing, powered by aesthetic values. Not an interest in the superficial appearance of the object, but a belief in an underlying object structure which mathematics or logic tries to capture. This pedagogy clearly emerged from Ulm, constituted a legacy of computational thinking that evolved till today. Its cultural and technological context requires the pursuing of a historical reading that would enhance the interpretation of architecture own contemporary history.

Endnotes

1. Extract from an interview with Tomas Maldonado conducted by the author for her PhD research on the Hochschule für Gestaltung Ulm (Milan, 9 October 2012).
2. Maldonado also says "kind of symbiosis of calculation and graphic representation Could be created within the process of problem solving is basic to the widespread present-day use of computer graphic techniques" (Lindinger, 1991).

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References

Bense, M.: 1972, *Introducción a la estética teórico-informacional : fundamentación y aplicación a la teoría del texto*, Alberto Corazon, Madrid.

Buchanan, R.: 2009, Thinking about Design: An Historical Perspective, *in* A. Meijers (ed.), *Philosophy of Technology and Engineering Sciences*, Elsevier, New York, 409–454.

Frampton, K.: 1974, Apropos Ulm: Curriculum and Critical Theory, *Oppositions*, **3**, 17–36.

Krampen, M. and Hormann G.: 2003, *The Ulm School of Design: Beginnings of a Project of Unyielding Modernity*, Ernst & Sohn, Berlin.

Krippendorff, K.: 2006, *The Semantic Turn: A New Foundation for Design*, Taylor & Francis, London.

Lindinger, H.: 1991, *Ulm design: the morality of objects*, The MIT, Cambridge, MA.

Maldonado, T.: 1958, Communication and Semiotics, *Ulm*, **5**.

Maldonado, T.: 1959, Glossário de Semiótica, *in* T. Crosby (ed.), *Uppercase 5 HFG Ulm*, Whitefriars, London.

Protzen, J.-P. and Harris, D.: 2010, *The Universe of Design: Horst Rittel's Theories of Design and Planning*, Routledge, New York.

Rocha, J. A.: 2004, Architecture Theory 1960–1980: Emergence of a Computational Perspective, PhD Dissertation, MIT, Cambridge, MA.

Rocker, I.: 2010, Emerging Structures: Information Aesthetics and Architecture of the Digital Medium, PhD Dissertation, Princeton University, Princeton, NJ.

Spitz, R.: 2002, *HfG Ulm and the view behind the foreground: the political history of the Ulm School of Design*, 1953–1968, Axel Menges, Stuttgart.

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SYMMETRY-BASED GENERATIVE DESIGN: A TEACHING EXPERIMENT

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Abstract. Throughout history, symmetry has been widely explored as a geometric strategy to conceive architectural forms and spaces. Nonetheless, its concept has changed and expanded overtime, and its design exploration does not mean anymore the generation of simple and predictable solutions. By framing in history this idea, the present paper discusses the relevance of exploring symmetry in architectural design today, by means of computational design and fabrication processes. It confirms the emergence of a renewed interest in the topic based on two main ideas: On the one hand, symmetry-based design supports the generation of unique and apparent complex solutions out of simple geometric rules, in a bottom-up fashion. On the other hand, despite this intricacy, it assures modularity in the design components, which can bring benefits at the construction level. As the background for testing and illustrating its theoretical arguments, this paper describes the work produced in the Constructive Geometry course at FAUP.

Keywords. Geometry; symmetry; computational design; digital manufacturing; education.

1. Introduction

Symmetry[1] is an old ordering principle that has inspired and explained the developments in many different scientific and artistic fields, like physics, biology or architecture. Nonetheless, its meaning has changed and expanded overtime, moving from the classic concern with prescribing ideals of harmonious proportion and beauty, to the modern sense of order resulting from the application of geometric transformations to an object, since they keep it invariant. While the former meaning is permeable to the aesthetic and cultural values of each place and time, the later is a precise and stable concept to describe the structure of formal systems (i.e. natural, built, abstract…), unfolding either in the (two dimensional) plane or in the (three dimensional) space.

Implying the application of isometric transformations, the list of basic symmetries are: Rotational symmetry, reflection symmetry (bi-lateral), Rotoreflection symmetry, Central inversion symmetry, Translation symmetry, Glide reflection symmetry, Helical symmetry. In any possible combination of those geometric transformations, both the shape and the measures of a transformed object are kept invariant.

However, if one accepts other possibilities for variation, then it is possible to distinguish non-isometric symmetries in other geometries, as it was systematized in the Erlangen program, by Felix Klein in 1872 (Devlin, 2003, p. 152). These variations can thus unfold through more elaborated symmetric transformations like similarity, affine, projective and topological ones (March and Steadman, 1971, p. 25)

In this context, this paper argues that there could be two modes of approaching symmetry: an analytical and a generative. When studying an existing object, like a platonic solid, its shape can be described from the symmetry point of view. In a top-down manner, one can explain a solid by identifying the set of its constituents (parts) and subsequent geometric transformations that originated it. For instance, the cube can be described by a group of rotations of a square in space around a common central point. This kind of analysis is thus essentially descriptive, and it is intimately linked to the mathematical concept of symmetry groups, proposed by Evariste Galois in the early XIXth century (Devlin, 2003, p. 146). In a different way, when performing a creative task, symmetry can be explored in a bottom-up manner. Instead of looking at a pre-conceived form and decomposing it, the attention is now focused on the application of geometric transformations to an initial form as a way to conceive an original one. Here, symmetric transformations are used as a generative engine to discover of new design possibilities. In other words, the shape is not itself the search space, but the starting point to entail a morphogenetic evolution that can give rise to other configurations and combinations. The application of spatial rotations to a square can generate not only the cube, but also other solids, like the triangular prism, the cuboctahedron or the rhombicuboctahedron, among others (Figure 1). This structured generative aspect is of critical importance for a designer, as acknowledge by Stiny, when outlining a *constructive* approach to the definition of languages of design (1980), or by Knight's works and overview on the shape grammars field (1999).

2. Symmetry in Architecture

Throughout the history of architecture, symmetry has been widely explored as a geometric concept to describe and conceive architectural forms and spaces, following the two meanings described earlier.

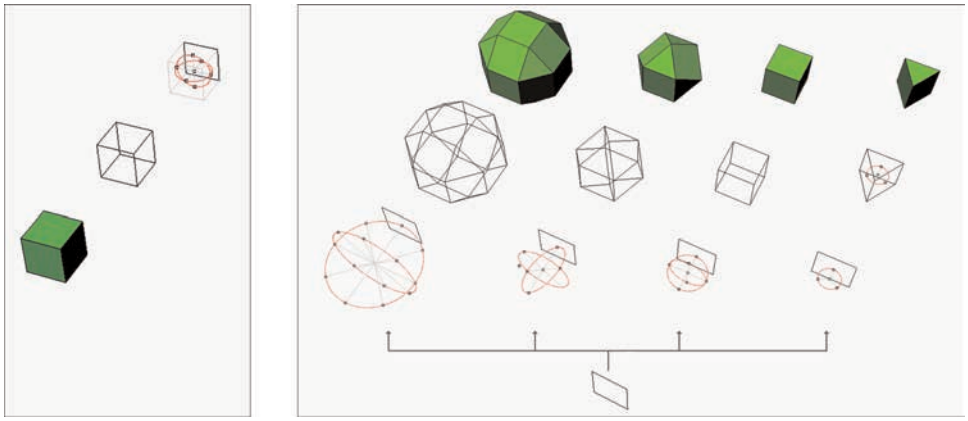

Figure 1. The analytical (top-down) and the generative (bottom-up) approach to symmetry in design. On the left, a cube is described through the implicit rotation of a square in space. On the right, exploring the rotations in space of a square can lead to the generation of different figures (the rhombicuboctahedron, the cuboctahedron, the cube, and the triangular prism).

Back to the ancient Greece, symmetry meant the definition of a harmonious system of proportions, or ratios, between the whole and its parts of an object. Following this understanding, Vitruvius recommended the architectural importance of symmetry for the design of a Temple[2], and triggered a long tradition in the discipline where the ideal of beauty and perfection were assured by means of symmetric structures and compositions. Despite some minor different conceptual motivations (e.g., religious, philosophical, psychological…), this notion prevailed in the theory and practice of architecture, through the Renaissance and until the XVIIIth century (Von Meiss, 2004, p. 65). It was clearly expressed by influent architects like Alberti or Palladio, and can be read in the dominance of reflection and rotational symmetry in the design of buildings, especially in those with public importance[3].

When theorizing about the impact of modern science in architecture during the XVIIIth century, Pérez-Gómez (1983) describes a set of cultural and technological facts that contributed to a paradigm shift in the way man saw and comprehended the world. With particular relevance for this paper, the appearance and systematization of non-Euclidian geometries in mathematics prompted the development of a general and rational theory about symmetry, based on groups of geometric transformations. The modern scientific advancements of this period brought cultural and technological changes, which naturally affected the discipline of architecture and its values. Like Perrault, several influent architects reacted to tradition, detaching symmetry from proportion, and subjective ideals of beauty and harmony[4].

For instance, while J.N.L. Durand recommended the use of symmetry, together with regularity and simplicity, just as a way to achieve economy in building construction[5], others, like Viollet-le-Duc, argued that balance and proportion could be achieved by means of asymmetric formal and spatial compositions[6].

Since then, the architectural evolution during the last two centuries has revealed an expansion of formal languages towards an increasing degree of geometric freedom. Conventional reflective or rotational symmetry as privileged compositional rules gave place to more elaborated geometric arrangements, either of symmetric (isometric and non-isometric) or asymmetric order. The modern movement, the deconstructivism trend in postmodern architecture, or the recent exploration of free-form buildings enabled by computer technologies, are just three of the tendencies that have challenged the traditional notions of balance, order and proportion. Many theorists and architects since Viollet-le-Duc have pointed several contradictions in symmetry, which lead to a progressive decrease of interest in the discipline[7]. Klaus Mainzer resumes the current tendencies happening not only in architecture but in the modern globalized world as a move from symmetry to complexity, where the platonic union of truth and beauty is broken and transformed into diversity and heterogeneity (Mainzer, 2005, p. 329).

3. Symmetry as a Generative Design Strategy

In the last thirty years, the world has witnessed the rise and influence of computer technologies in almost all aspects of our life. In architecture, the use of digital design (CAD) and manufacturing (CAM) technologies have dramatically expanded the creative space of design and construction possibilities[8]. While the use of advanced 3D modelling allows for the easy and rigorous representation in the screen of 3D complex forms, the use of computational design processes[9] allows for the interactive calculation of geometric variation and evolution. Facing this design flexibility, the employment of CAM technologies offer solutions for materializing complex geometries and exploring mass production logics based on customization. This digital continuum from design to production has drew a new paradigm in architecture, where design representation and construction are no more limited by formal complexity and repetition, as it happened until then. Thus, in a moment when contemporary architecture experiences an increasing geometric freedom at many levels, why does a traditional and, apparently, old-fashion subject like symmetry could be of interest for architects?

Considering the mathematical notion of symmetry, its actual relevance in architecture seems to reside in its generative potential for design rather than on its descriptive. If one agrees that its creative dimension is tied to the capacity of rep-

resentational tools to describe and calculate transformations over a form then, the impact of current digital design processes on symmetry should not be ignored. The move from explicit design tools, either analogical or digital, to computational design ones has allowed the exploration of symmetry in ways that would be difficult in the past. By stating that "*computers discover symmetry of invariant structures hidden behind the appearance of chaotic attractors*" Mayer (2005, p. 385) establishes a direct and inspiring relation between symmetry and complexity. Thus, when architects employ parametric and algorithmic strategies to describe iterative and recursive sequences of symmetric transformations in space, the evolution of an initial geometry can lead to unpredictable solutions, in a constant dialogue with digital interactive models. The idea of symmetry as a generative principle leading to monotonous and obvious configurations, may be surpassed by taking advantage of the calculation power embedded in computational design processes, either through software-based or programming approaches. Spanning over isometric and non-isometric invariants, it seems also reasonable to question if symmetry is not laying at the core of most parametric design approaches in contemporary architecture.

4. The Teaching Experiment (Isometric Symmetry)

To investigate and test the arguments described above, this paper is now focused in isometric symmetry, which is the most regular and predictable scenario. To illustrate the contribution of computation to embrace it as a generative strategy, it will be presented a teaching experiment developed during the Constructive Geometry course at the Faculty of Architecture of the University of Porto[10]. Named as "Parametric Symmetry", this assignment looked for generating reconfigurable symmetrical forms using Grasshopper, the parametric design plug-in for Rhinoceros software.

Implying an important shift in representation and thinking processes, it was important to introduce the students to computational design thinking prior to the design techniques. Among several theoretical and practical examples, D'Arcy Thompson still offers today a clear source of reference about the creative link between mathematics and design, when he mentions that "*we are apt to think of mathematical definitions as too strict and rigid for common use, but their rigour is combined with all but endless freedom. The precise definition of an ellipse introduces us to all the ellipses in the world*" (Thompson, 2000, p. 269). By centring their focus on the implicit geometric definition of form(s) instead of on the explicit features, the students were ready to develop the assignment and embrace the technique in a proper way. As an additional note, given the nature of the course, the exercise rejected the involvement of any programmatic design concerns. The goal

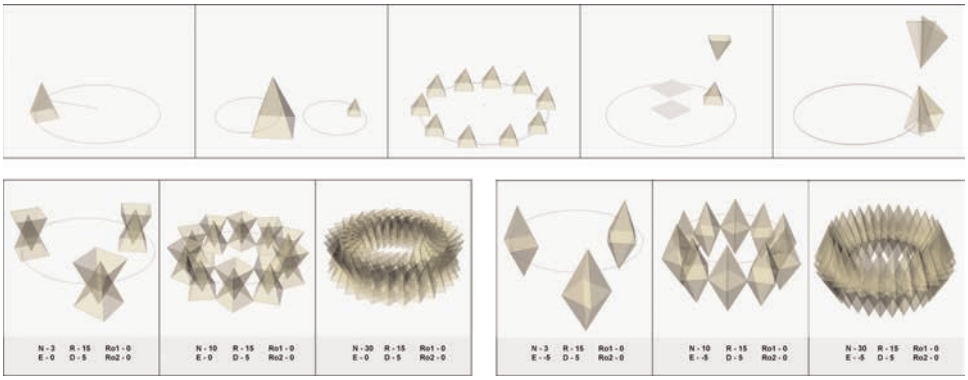

Figure 2. On the top, the definition of parametric transformations on a pyramid. (from the left: circular rotation in the plane; uniform scaling; replication on a circle; reflection from an horizontal plane with changeable height; spatial rotation). On the bottom, two examples of parametric variation.

was to approach the subject on an abstract and mind-opened way, which could further serve to guide its multi-scalar application to address architectural or even urban planning problems.

In this context, each student had to select an initial object (a group of surfaces or a solid) and program, in Grasshopper, the parametric application of a set of symmetric transformations over it (Figure 2).

To guide this investigation, two premises were given:

- the initial object should be simple;
- the symmetry explored should be isometric.

Both of these conditions were important to facilitate, in the end, the perception of the degree of complexity that was introduced by the (generative) process rather than by the specificities of the initial form. To prove their control over the design exploration, the students had to make a physical model of one possible solution generated by their parametric definitions (Figure 3).

The “Parametric Symmetry” experience resulted in a diversity of symmetric models emerging from the application of different sequences geometric transformations, both in the plane and in space. Although just one solution was materialized, the students had to explain the parameters controlling their generative model and map, with the help of tables, the spectrum of variation of possible solutions. During the work, there was a common sense that dealing with parametric models was an interactive experience where each one could express and evolve

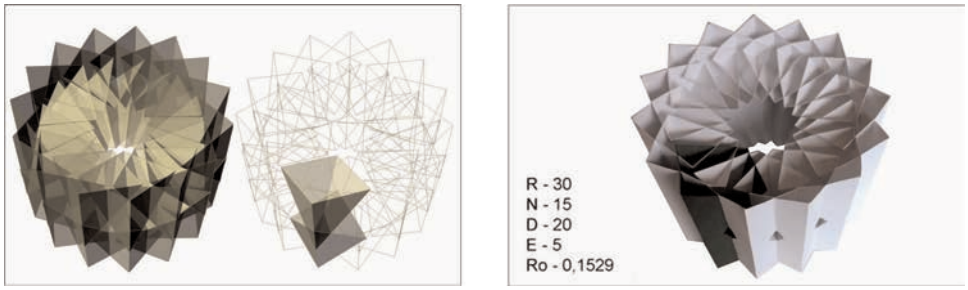

Figure 3. Digital and material comparison of one computationally generated symmetric de-sign. The modular component is identified in both pictures.

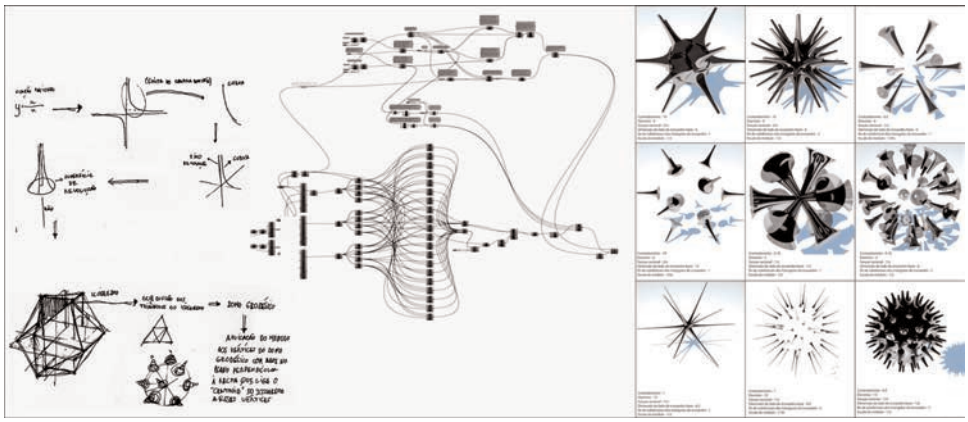

Figure 4. Design thinking and definition evolve through the interaction of mental, analogical and digital processes.

their design intuitions (Figure 4). The visual and interactive programming with Grasshopper revealed to be very helpful to support design thinking and decision making along the process. The behaviour and results obtained out of simple rules was frequently surprising enough to motivate design changes towards novel and unexpected directions.

It was also interesting to notice that, at a certain point, almost every student claimed for the introduction of metric variation on the model. Nonetheless, although it was not difficult to start adding non-isometric transformations to the model, they were forced to resist such intentions in the assignment to really test the generative potential of symmetry only by using isometric transformations. In the end, independently of their apparent complexity, all parametric models and constructions developed can be described and physically made out of the repetition of

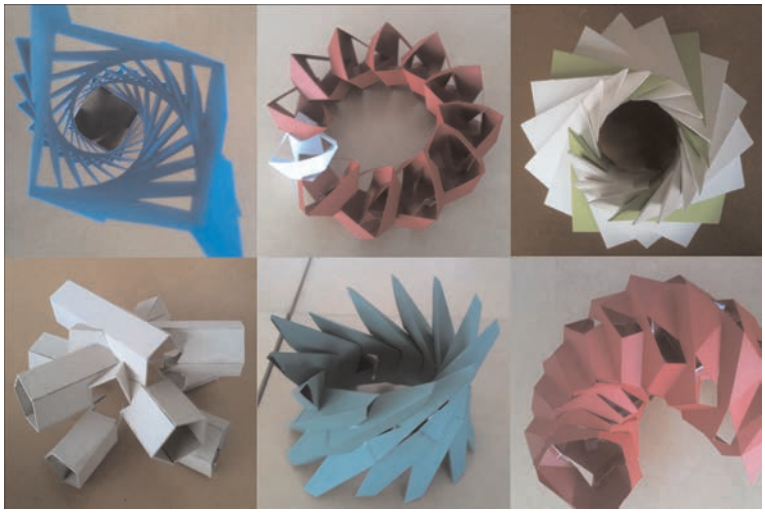

Figure 5. Physical models produced out of isometric transformations.

a modular (standard) element. The geometric exploration of symmetry can thus benefit a lot from design computational processes, which can foster a renewed interest in contemporary architecture (Figure 5).

5. Conclusion

Besides exploring new opportunities, the current evolution of architecture by means of digital technologies is also occurring by looking at the past. Motivated by the use of computers in practice, we have assisted to a renewed interest in architects from the past, like Vitruvius, Alberti, Palladio, Gaudi, Eladio Dieste, Buckminster Fuller or Frei Otto, just to name a few of them[11]. Hence, it is aligned with this kind of interest that this paper looked at the topic of symmetry with the goal of contributing today for rethinking such a classic topic of the architectural history.

As it was described and illustrated with the teaching experiment, the use of computational design tools to investigate symmetry has proved to be a creative window to achieve geometric complexity out of a finite set of very simple transformation rules. By proceeding this way, although the design process becomes structured and easily traceable, its outcomes are not easily imaginable *a priori*. This generative ability of simple rules producing rich results suggests an idea of productive economy in the design process, which can be expanded to the construction level. In fact, after an industrialization ruled by mass production logics

based on standardization, current digital design and manufacturing technologies are supporting the current move towards the production of singular objects with unique forms and customized building solutions. Thus, in a moment where contemporary architectural discourses balance between doing *everything the same* or *everything different*, exploring symmetry through digital means seems a powerful design strategy to negotiate the best of both tendencies[12].

While we have focused in the teaching experiment on isometric symmetry, a complementary paper is under preparation to extend the illustration of this subject into the world of non-isometric symmetries.

Endnotes

1. Symmetry has its origins from the Latin term *symmetria* and the greek *symmetros*, and generally means "having a common measure".
2. Vitruvius recommends that "the design of a Temple depends on symmetry, the principle of which must be most carefully observed by the architect", and makes evident the classic notion of symmetry by saying that "proportion is a correspondence among the measures of the members of an entire work, and the whole to a certain part selected as standard. From this result the principles of symmetry" (1998, p. 72).
3. A detailed account on the contributions of classic and renaissance architects on the subject of symmetry can be read on Wittkower (1971) and Pérez-Gómez (1983).
4. It is significant that, according to Mitchell, "when Claude Perrault published his French translation of Vitruvius (1673), he rendered symmetria as 'proportion'" (Mitchell, 1998, p. 30).
5. Jean-Nicolas-Louis Durand insisted about the importance of geometry to achieve economy in building construction which was, together with fitness, the two guiding concepts for the discipline (Durand, 1999, p. 88)
6. Referring that "Viollet-le-Duc was constantly inveighing against the ´banal rules of symmetry'", R. Etlin explains how he argued that, in an asymmetrical design, "through the skillfull (...) ponderation of masses the architect could achieve a 'subtle system of harmony'" (Etlin, 1994, p. 82). Asymmetry became thus understood as another possible principle to achieve order and balance.
7. P. Von Meiss refers to the devaluation of symmetry through its popularization during the XIXth century, which led, during the XXth century, to the emergence of asymmetry as a valid way to "achieve buildings representative of authority or religion" (Von Meiss, 2004, p. 65). In science, the interaction of intrinsic and extrinsic forces started to explain the generation of a diversity of forms out of common formal principles (Pearce, 1990, p. xiv). The acknowledgement of symmetry breaking processes occurring in nature fostered the acceptance of asymmetrical balance. On this respect, G. Lynn argues that "Symmetry is not a sign of underlying order but an indication of a lack of order due to an absence of interaction with larger external forces and environments" (Lynn, 1998, p.70). Thus, besides losing its symbolic authority, symmetry became unsatisfactory to negotiate the design of buildings with the heterogeneity of the contextual environment. R. Venturi expands this idea in its *Complexity and Contradiction in Architecture* work.
8. This observation is extensively discussed and illustrated in B. Kolarevic book (2003).
9. Computational design implies the use of digital design processes that merges calculation in representation by means of parametric and algorithmic processes. Terzidis (2006) describes and opposes this concept to that of computerization.
10. The Constructive Geometry course is dedicated to investigate the impact of computational design and digital fabrication processes in architectural geometry.

11. One could mention here William J. Mitchell, George Stiny or Larry Sass works on Palladio, Mario Carpo review of Alberti, Bernard Cache focus on Vitruvius, Mark Burry work in-practice about Gaudi's legacy at the Sagrada Família, or Achim Menges and Lars Spuybroek inspiration on Frei Otto work. In Portugal, a current work about Alberti has been conducted by Mário Krüger and José Pinto Duarte.
12. When designing and building variation is possible through digital processes, the building logistics may be taken into account to prevent the project failure. Therefore, given that isometric symmetry still keeps modularity in the design of components, it can bring benefits at the construction level (e.g., making easier storage, transportation or assembly processes).

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References

Devlin, K.: 2003, *Mathematics: The Science of Patterns*, Henry Holt, New York.
Durand, J. N. L.: 1998 (1st ed. 1809), *Précis of the Lectures on Architecture*, Reprint, The Getty Research Institute, Los Angeles.
Etlin, R.: 1994, *Frank Lloyd Wright and Le Corbusier: The Romantic Legacy*, Manchester University, Manchester.
Knight, T.: 1999, "Applications in architectural design and education and practice", Report for the NSF/MIT Workshop on Shape Computation MIT. Available from <http://www.shapegrammar.org/education.pdf> (accessed January 2013).
Kolarevic, B. (Ed.): 2003, *Architecture in the Digital Age: Design and Manufacturing*, Spon, New York.
Lynn, G.: 1998, The renewed novelty of symmetry, *in* G. Lynn, *Folds, bodies & blobs: Collected Essays*, La Lettre Volée.
Mainzer, K.: 2005, *Symmetry and Complexity. The Spirit and Beauty of Nonlinear Science*, World Scientific.
March, L. and Steadman, P.: 1971, *The Geometry of the Environment*, RIBA, London.
Mitchell, W. J.: 1998, *The Logic of Architecture. Design, Computation and Cognition*, MIT, Cambridge, MA.
Pearce, P.: 1990, *Structure in Nature is a Strategy for Design*, MIT, Cambridge, MA.
Pérez-Gómez, A.: 1983, *Architecture and the Crisis of Modern Science*, MIT, Cambridge, MA.
Stiny, G.: 1980, "Kindergarten grammars: designing with Froebel's building gifts", in *Environmental and Planning B*, Vol.7 (pp. 409–452).
Terzidis, K.: 2006, *Algorithmic Architecture*, Architectural, Oxford.
Thompson, D.: 2000 (1st ed., 1917), *On Growth and Form*, Reprint, Cambridge University, Cambridge.
Vitruvius: 1998 (1st ed., 1st century BC), *The Ten Books on Architecture* (translated by M. H. Morgan), Reprint, Dover Publications, New York.
Von Meiss, P.: 2004, *Elements of Architecture. From Form to Place*, Spon, London.
Wittkower, R.: 1971, *Architectural Principles in the Age of Humanism*, W. W. Norton, New York.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 313–322. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

A FRAMEWORK FOR SOCIAL NETWORKED ARCHITECTURAL EDUCATION

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Abstract. Students engage in Social Networks (SN) as a form of interaction with friends and tutors, as news or learning resource, to make their voices heard or to listen to other views and many more. Online SN work in close association with offline SN to form a blended social environment that greatly enables and enhances students' learning. Some Schools of Architecture have struggled or failed to engage in the potential of SN or their respective University's online Learning Management Systems (LMS). Despite efforts to facilitate blended learning environments or to engage students in problem-based learning activities architectural education often fails to tap into the rich resources that online social learning environments offers through their collective and social intelligence of its users. This paper proposes a framework for SN architectural education that provides opportunities for linking the academic LMS with private or professional SN such that it enhances the learning experience and deepens the knowledge of the students. The paper proposes ways of utilising SN supported learning environments in other areas of the curriculum and concludes with directions of how this framework can be employed in professional settings.

Keywords. Social networks; social learning; architectural curriculum.

1. Introduction

We argue that there may be a failure of Schools of Architecture to engage in the potential of Social Networks (SN) to enhance education. This is because they may treat the students' online social experience as separate to their on-campus social learning experience. Despite efforts to facilitate blended learning environments or

to engage students in problem-based learning (PBL) activities, there appears to be untapped potential in relation to accessing the rich resources that a social learning environment offers through the collective and social intelligence of its members (Mason, 2012).

In the very recent past there have been various studies investigating the integration of Web 2.0 tools into learning within and outside of the discipline of the built environment. Wang et al. (2012) presents five core areas of application (using Web 2.0 demonstrates the capability for effective learning, skills learned via Web 2.0 can be transferred to other tasks and areas, limited research has compared learning in conventional E-Learning and Web 2.0 environments, E-Learning 2.0 enables social learning process to take place, and moving from eLearning 1.0 to E-Learning 2.0 requires a technological shift and a shift in the way knowledge is socially constructed & shared).

This paper addresses this issue and proposes a framework for social networked architectural education that provides opportunities for linking the academic with private or professional SN in such a way that it enhances the learning experience and deepens the knowledge of the students.

The focus of much research has been on the role of educational technologies to support, enhance and advance architectural education (Hirschberg, 2003; Gu *et al.*, 2010). Since the initiation of digital technologies into the design studio and other areas of the academy, a complex 'educational technology landscape map' (Smithers, 2010) has evolved (Figure 1). We argue that educational technologies are contingent on, and indeed useless without, an understanding of the social aspects of the educational environment.

The paper focuses on social aspects of architectural education and draws upon previous research in the areas of the Social Networked Virtual Design Studio (SNVDS) (Ham and Schnabel, 2012) and Social Networked Construction Technology (SNCT) (Ham et al., 2012) teaching. The paper expands these to propose ways of utilising SN, their media and interaction platforms in other areas of the architectural curriculum, such as communications, history, theory and professional praxis. The framework outlines an open system of learning that utilises SN to crowd-source, flatten hierarchies, facilitate social engagement and peer learning and expands the learning experience beyond the academic context to include other institutions, practices and professions. Our framework can be employed in inter-professional environments and hence can contribute to academic and professional education.

2. Precedents in Social Network Integration

Key components in the framework for social networked architectural education are peer learning, sharing of knowledge, and flattening hierarchies through the use

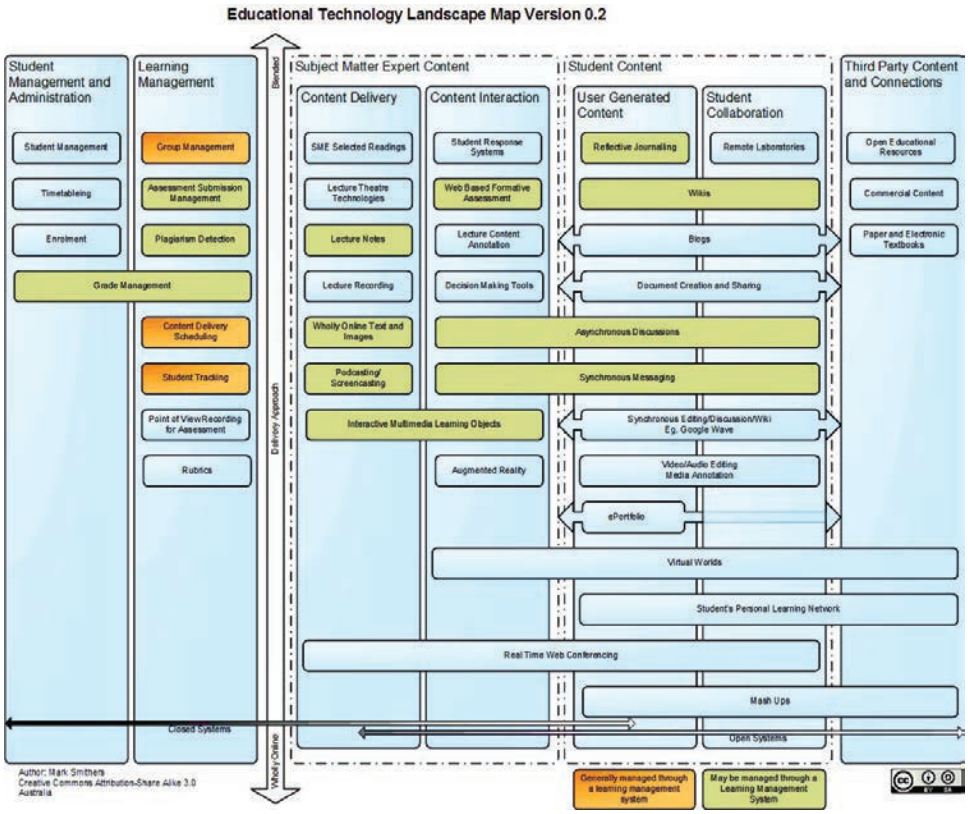

Figure 1. Educational Technology Landscape Map (Smithers, 2010).

of digital technologies. Significant precedents exist in these areas in research (Minocha, 2009; Rennie and Mason, 2008).

Over the past two decades the Virtual Design Studio (VDS) evolved as a learning environment that allows students in various locations to engage synchronously and asynchronously in design learning. VDS have facilitated collaboration across multiple boundaries and helped re-define the social and cultural contexts of the design studio. New technologies allow the VDS to evolve into new directions – some of which address shortcomings identified in past research. The VDS established virtuality as acting while physically distant, as acting by employing digital tools, or employing virtual instruments or other virtual components. Virtual Environments (VE) were established by the choice of design, way of communication or digital tools; later the VDS developed into real immersion within a VE, the medium for design interaction being the immersive VE Design Studio (VeDS)

(Schnabel and Ham, 2011). In all these samples, (online) social interaction through the design interaction was important to the learning and engagement with the design. The social communication was enabled through chat windows, emails, blogs and posting sites, wikis and other online communication tools. However these VDS did not recognise the social engagement as crucial or central to the overall process of construction of knowledge.

SN were first used in design, construction technology and inter-professional teaching as a means of engaging students in architectural education socially outside of the limitations of the University's LMS. These limitations include the development of silos of knowledge, lost opportunities for students to engage with each other and industry sources and limited sharing of resources for design decision support (Ham, 2010).

The Social Networked Construction Technology unit (SNCT) comprises a logical formation of the evolving streams of 1:1 construction and resource creation for design decision support as a means of engaging students as 'amateur researchers' in a way that ensures 'that student research work is worth more than course assessment' (Burry et al., 1995). The construction of knowledge was brought together within a social network through engagement in online blogs, YouTubeTM and FacebookTM (FB). The SNCT is based on 'authentic curricula…that allows students access to the real world of construction technology whilst utilising digital media and the Internet to enhance the process' (Ham et al., 2012).

With the advent of Web 2.0 technologies, the next logical step was to develop the VDS was collaboration within a SN (Howe and Schnabel, 2009). Ease of communication, leadership opportunity, democratic interaction, teamwork, and the sense of community are some of the improved aspects that are offered by SN (Owen et al., 2006). Mitchell (1995) also refers to the need for an on-going evolution of the VDS towards a fully integrated studio where the borderlines between realms, professions, tools and mode of communications are dismantled. Subsequently the advancement of VDS moves design education beyond conventional boundaries and curricula, and engages participants socially from diverse professional fields.

The Social Network VDS (SNVDS) is subsequently the successor of the VDS and has operated over various design studio curricula since 2009 (Ham, 2010). The key to the SNVDS is engaging with the nomadic device generation whilst facilitating social engagement in the form of 'casual interaction online, leading to casual interaction offline' (Barkhuus and Tashiro, 2010). Through the encouragement of a flattened hierarchical structure between students and staff, the teacher's role changes from 'the sage on the stage to the guide on the side' (King, 1993). These flattened hierarchies create opportunities for collective intelligence,

wherein opportunities for information can be shared among social groups, extending beyond the conventional studio setting. From collective intelligence comes collective social intelligence that relates to both the current design project as well as knowledge in the relevant fields. The SNVDS differs from traditional model of delivery in that the students themselves became the primary contributor to skills, content, and knowledge required for the design project (Ham and Schnabel, 2012). It also differs from conventional PBL due to the difference of scaffolding and problem framing (Howe and Schnabel, 2012).

3. Models of Social Network Interaction at University

SN are defined as a 'theoretical construct useful in the social sciences to study relationships between individuals, groups (and) organizations' (http://en.wikipedia.org/wiki/Social_network). They form the core of the student University experience and, we argue, are secondary to elements of the educational technology map by Smithers (2010).

We identify and focus on four modes of SN related to the University experience; social-physical networks (SP), social-digital networks (SD), learning-physical networks (LP) and learning-digital networks (LD). These social network modes exist concurrently and intermesh with each other synergistically throughout the student University experience.

Social-Physical networks take the form of social groups of family and friends centred outside of the University environment. These may comprise of immediate and distant family groups, as well as school and work friends. The basis of these networks is normal face-to-face human interactions between the student and other people.

Social-Digital (SD) networks extend social-physical networks into the online environment through a wide range of channels including Facebook™ (friends, 'likes', groups, etc.), Google+™, Twitter™, Tumblr™, YouTube™, and Blogs.

Learning-Physical (LP) networks are networks of friends, class mates, group-work colleagues, teachers and others connected to each other within the on-campus University learning environment. The University learning experience forms the basis of these networks through shared design studios, classes, group project work and extra-curricular activities.

Learning Digital (LD) networks are digital networks set up within the University environment for the express purpose of facilitating and enhancing teaching and learning. These are generally centred around some form of Learning Management System (LMS) such as BlackBoard™, Desire2Learn™ and Moodle™ but also include online learning resources such as web sites and other digital aides to teaching and learning.

Direct synergies occur between SP and SD networks, where a complex series of face-to-face interactions take place, are enhanced by or facilitated by SD networks. The SD network acts as an extension of both the SP and LP networks, thus lines between digital and physical, social and learning networks become blurred. Concurrently, students engage in digital SN to create and extend forms of social interaction with friends, as a news service, to make their voices heard and as a form of entertainment. Online SN work in close association with offline SN to form a blended social environment that greatly enhances students' University experience. The blended learning, here, represents a blending of social experiences as well as a blending of educational technologies.

In the current model of social network interaction (Figure 2), interactions between SP, SD, LP and LD networks can be conceptually represented with the student at the centre. Interactions between SP, SD and LP networks are strong, as are interactions between LP and LD networks.

The University has however, through the focus on the corporate LMS, created a barrier between the LD network and SP and SD networks. Barriers exist because of the typical 'paying students only' access to the LMS, separate course and unit structure and the reinforcement of learning silos (Alexander, 2006) nature of the LMS disallowing linkage between units thus creating or enhancing knowledge silos between subject areas and elements of the University learning experience (Figure 3).

To compound these problems, some Universities have failed to engage in the potential of SD networks as an important channel of two-way communication between staff, students and others (including the Industry). Failure to engage takes the form of non-engagement or improper engagement in digital SN. Schools of Architecture have set up Facebook-sites as a unidirectional means of communication

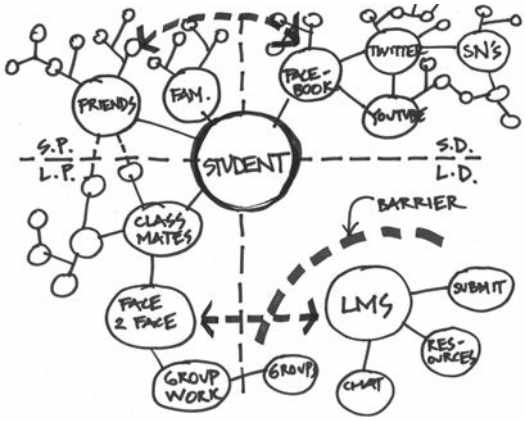

Figure 2. Current models of Social Networks Interaction at University.

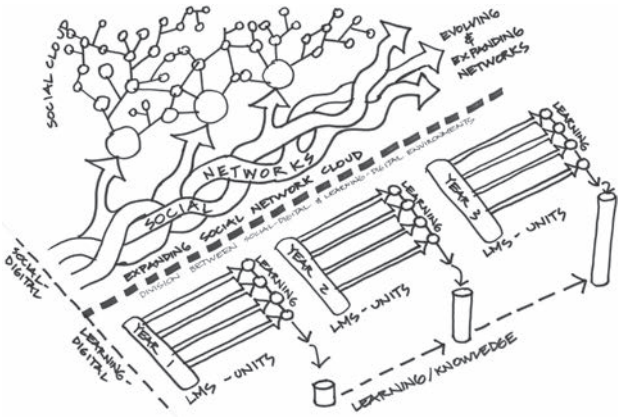

Figure 3. The current divide between SD and LD networks.

of news; however this mode of social media use is based on the assumed need to control communication and simply replicates the capacities of a website.

In our experience, the University's enforcement of the LMS and email as the sole means of LD networking is firmly entrenched. Pressures of increasing student numbers, shortened preparation times between trimesters and other factors provide a disincentive to engage in the potential of bringing together the SD and LD networks (Schnabel and Ham, 2011). We believe that this does not meet the needs or aspirations of social-media savvy students engaged in the learning experience (Robbins-Bell, 2008).

4. A Framework for Social Networked Design Education

We anticipate the re-conceptualisation of the current model of SN integration at University to increase linkages between the SP, LP, SD and LD networks. This is achieved by developing a student-centred approach that attempts to break down the barrier between the University LMS and other aspects of the students' SN and integrates social networking to the core of the curriculum (Figure 4).

Any reconceptualization of the role of social networking in the learning experience can be achieved through "Just in Place" learning systems (JPL) (Punnen, 2010). These are 'composed of virtual information layered on top of physical artefacts and made available through different social media outlets/ technologies. JPL brings together ubiquitous and calm computing models (Weiser and Brown, 1996), social and immersive media (Shirky, 2009; Snibbe and Raffle, 2009), and situated technologies (Shepard, 2009) in a way that friendship-driven networks and interest-driven networks intersect.

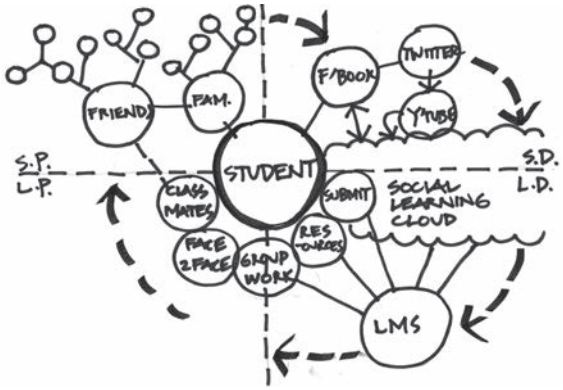

Figure 4. Reconceptualised model of Social Networks Interaction at University.

'Thus, information can now be pulled from various sources and consumed and produced asynchronously and/or synchronously in a chosen place and/or time. In addition, new smart mobile technologies also mean that we now have the ability to retrieve (and expect) just in time, and just in place information' (Riel, 2000).

Through re-positioning the SP, LP, SD and LD networks through JPL, a framework can be developed based on the evolution of a 'Social Learning Cloud' (SLC). Here, the silos of the LMS-driven curriculum are set aside through the integration of the concurrent learning streams in the curriculum. Through active engagement in multiple SN, learning becomes a two-way experience: students act as both learners and researchers contributing to the body of knowledge in a way that '*that student research work is worth more than course assessment'* (Burry et al., 1995). Figure 5

Figure 5. Re-conceptualising SD and LD networks around a SNC learning environment.

shows how a SNC enabled learning environment facilitates seamless learning between the rigour of various units or years and the construction of knowledge in a larger context. SNC enables life-long learning and authentic learning experiences, because content, participants and other (outside) sources form the network that has no boundaries of a specific course or subject.

5. Conclusion

We present a framework for SN engaged learning as a form of interaction with peers, friends and teachers, as learning environment. A SNC system forms herby the core of a blended environment that intersects between on- and offline learning as well as blends between the boundaries of individual units, courses, years and the lifelong learning in authentic contexts, subsequently greatly enabling and enhancing students' learning experiences. The positive experience we gained within the curriculum of the architectural degree we propose to transfer this framework to other disciplines, which lays in the nature of SN acting independent of core-subjects or academic or professional realms. LMS, blogs or interest groups have failed since they don't offer seamless interaction, from the individual to the network and only act as point to point or point to group communication. Hence SNC facilitate 'cloud learning' – the interaction of particles within cloud; flow – the seamless acquisition of knowledge; synchronous and asynchronous learning modes – enabling of JTL; 'knowing is there' and 'knowing it' – both access to knowledge and deep learning; and identity – the need of learners to belong to an environment that matches the level, skills and communication of the individuals.

References

Alexander, B.: 2006, Web 2.0: A New Wave of Innovation for Teaching and Learning? *EDUCAUSE Review,* **41**(2), 32–44.

Barkhuus, L., and Tashiro, J.: 2010, Student Socialization in the Age of Facebook, *Proceedings of CHI*, ACM Press, 133–142.

Burry, M., Prentice, R. and Wood, P.: 1995, Walking Before Running: A Prelude to Multimedia Construction Information, *Proceedings of the 13th International Conference on Education and research in Computer Aided Architectural Design in Europe* (eCAADe'95), Palermo, Italy, 257–266.

Gu, N., Jones, W. M., and Williams, A.: 2010, Utilising digital design and rapid prototyping tools in design education, *Proceedings of the 15th International Conference on Computer Aided Architectural Design Research in Asia,* CAADRIA, Hong Kong, 249–258.

Ham, J. J.: 2010, Working outside of the system: engaging in Web 2.0 to enhance learning and teaching in the design studio, *Proceedings of the 15th International Conference on Computer Aided Architectural Design Research in Asia,* CAADRIA, Hong Kong, 209–218.

Ham, J. J. and Schnabel, M. A.: 2012, How social is the virtual design studio? A case study of a third year design studio, *Proceedings of the 17th International Conference on Computer-Aided Architectural Design Research in Asia,* CAADRIA, Hong Kong, 173–182.

Ham, J. J., Schnabel, M. A., and Datta, S.: 2012, Developing Online Construction Technology Resources in Tectonic Design Education, *Proceedings of the 30th International Conference on Education and research in Computer Aided Architectural Design in Europe* (eCAADe'12), Czech Technical University in Prague, Prague, Czech Republic, 135–142.

Hirschberg, U.: 2003, Transparency in Information Architecture: Enabling Large Scale Creative Collaboration in Architectural Education over the Internet, *International Journal of Architectural Computing*, **1**(1), 12–22.

Howe, E. L. C. and Schnabel, M. A.: 2012, The Changing Face of Problem–Based Learning – Social networking and interprofessional collaboration, *in* S. Bridges, C. McGrath, and T. L. Whitehill (eds.) *Researching Problem based Learning in Clinical Education: The Next Generation*, Springer, The Netherlands, 121–138.

King, A.: 1993, From Sage on the Stage to Guide on the Side, *College Teaching*, **41**(1), 30–35.

Mason, W.: 2012, "Group Identity, Culture, and Collective Intelligence". Available from: Collective Intelligence Workshop, MIT, Cambridge, MA, <http://cci.mit.edu/ci2012/plenaries/speaker%20slides%20ci%202012/winter%20mason%20CI2012.pdf> (accessed 1 December 2012).

Minocha, S.: 2009, Role of social software tools in education: a literature review, *Education + Training*, **51**(5/6), 353–369.

Mitchell, W. J.: 1995, CAD as a Social Process, *Proceedings of the 6th International Conference on Computer-Aided Architectural Design Futures* (CAADFutures'95), National University of Singapore, Singapore, 7–9.

Owen, M., Grant, L., Sayers, S., and Facer, K.: 2006, Social software and learning. Futurelab, *HAL*, **1**, 1–36.

Punnen, M. A.: 2010, Just in Place Learning: A Novel Framework for Employing Information in "Place" for Urban Learning Environments, *Proceedings of the 30th Annual Conference of the Association for Computer Aided Design in Architecture* (ACADIA'10), New York, 73–80.

Rennie, F. and Mason, R.: 2008, *e-Learning and Social Networking Handbook;* London, UK, Routledge.

Riel, M.: 2000, Education in the 21st Century: Just-in-Time Learning or Learning Communities, *Education and the Arab World: Challenges of the next millennium*, Emirates Center for Strategic Studies and Research (Ed), Abu Dhabi, 137–160.

Robbins-Bell, S.: 2008, Higher Education as Virtual Conversation, *EDUCAUSE Review*, **43**(5), 24–36.

Schnabel, M. A. and Ham, J. J.: 2011, Web 2.0 virtual design studio: social networking as facilitator of design education, *Architectural Science Review*, Taylor & Francis, London, UK, **54**, 108–116.

Shepard, M.: 2009, Toward an Architecture of Hertzian Space, *Proceedings of the 29th Annual Conference of the Association for Computer Aided Design in Architecture* (ACADIA'09), Chicago, Illinois, 209-215.

Shirky, C.: 2009, *Here Comes Everybody: The Power of Organizing Without Organizations*, Penguin Press.

Smithers, M.: 2010, "A Draft Educational Technology Landscape Map". Available from: <http://www.masmithers.com/2010/06/28/a-draft-educational-technology-landscape-map> (accessed 1 December 2012).

Snibbe, S. S., and Raffle, H. S.: 2009, Social immersive media: pursuing best practices for multi-user interactive camera/projector exhibits, *Proceedings of the 27th International conference on Human factors in computing systems*, ACM, 1447–1456.

Wang, X., Love, P. E. D., Klinc, R., Kim, M. J., and Davis, P. R.: 2012, Integration of E – learning 2.0 with web 2.0, *Journal of Information Technology in Construction (ITcon)*, **17**, 387–396.

Weiser, M. and Brown, J. S.: 1996, Designing Calm Technology, *PowerGrid Journal*, **1**(1), 75–85.

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LEARNING WITH DIGITAL AND PHYSICAL MOCK-UPS USING BIM

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Abstract. Computer-based tools have changed the focus and modes of design thinking in architecture. While often criticized for its overemphasis on formal expressions and its pursuit of the spectacular, digital creativity has begun to take into account a multiplicity of design factors that define architecture. These factors relate to performance simulation and analysis, constructability, and building information modelling (BIM). This paper discusses the use of physical and digital mock-ups in the context of building technology courses. It uses these mock-ups as an important vehicle that provides students with a feedback mechanism regarding often digitally idealized creative thinking.

Keywords. BIM; building information modelling; parametric construction details; construction assemblies.

1. Introduction

Creating-making is a formative constant in the ways design thinking translates into the built environment. Creating-making transcends the division between technology and handmade products or, more recently, between analogue and digital modes of production. As during the Renaissance, when ideas expressed in drawings and sketches were tested with physical models[1] – mock-ups – similarly today we continuously shift between physical and digital modes of thinking and production. A significant difference today, however, lies in a tightly integrated dialogue between the physical and the digital. The digital is no longer a mere representation of the future physical (a proposed design), nor is the physical a mere realization of the digital creativity, fabricated from scale-less and context-less digital models. The digital-physical design dialogue is more intricate and bidirectional, involving simulations, performance analyses, and component optimization.

This paper discusses the integration of physical and digital models in the context of the structure course in an accredited (professional) architectural program.

It presents the student work that explores the design possibilities of a chosen structural system with the use of parametric and behaviour-based computational modelling. It uses the mock-up as a vehicle to study, optimize, and evaluate the design as well as to provide feedback for student learning. Finally, it investigates digital-to-physical design translations, the importance of which becomes more and more critical in the context of the current, computer-intensive education of architects.

2. Class Methodology

The class approach employed a long tradition of using physical models to evaluate design ideas.[2] However, this long tradition has a new variable – computation – that opens unique design opportunities and resolves some limitations associated with the use of physical models as design evaluators in the past.

For the term project, students were asked to investigate a structural system that actively informed architectural tectonics (form-active structures) and to explore its design possibilities with the use of parametric and/or behaviour-based computational modelling. Later, students were asked to build a physical mock-up of the final design and compare it with computer simulations they developed earlier for the same design. Students were asked to follow these steps in the development of a term project:

- Choose a structural system that actively informs architectural tectonics through kinetic behaviours, or material simulations.
- Research relevant precedents and pay special attention to assembly details and kinetic mechanisms that can be used as departing points for design explorations.
- Develop digital models (mock-ups) using parametric geometries and/or physically based simulations.
- Test alternative designs through digital simulations.
- Build a large-scale physical mock-up and verify design assumptions from digital simulations.

The purpose of the assignment was twofold: to bring to students' attention the materiality aspects of digitally designed architecture, with an understanding of the opportunities and limitations various design tools give us, and to visualize structural behaviour in more intuitive and direct ways.

3. Scissors and Hinges

An example of kinetic assembly is a façade screen system (Figure 1) that builds on the precedent of Chuck Hoberman's work and the façade screens of the Institute du Monde Arabe in Paris. Students developed a number of physical and computational models to test design variations and ultimately proposed a number of two- and three-dimensional alternatives to the conventional scissor-like hinge assembly. The

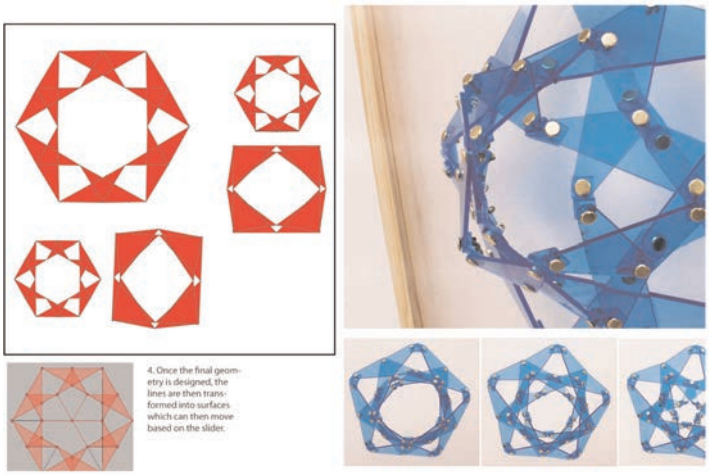

Figure 1. Façade screen mock-ups.

physical and digital explorations were full of surprises and discoveries. What seemed like a straightforward design quickly became a complex project, particularly when multiple instances of a scissor mechanism were interconnected into larger assemblies. The connection details also became more intricate, with divers rotation and sliding motions occurring within the assembly. Some of the design explorations led students into three-dimensional versions of the base mechanism that resulted in dome-like assemblies. Students had to develop additional wedge-like adapters to control the curvature of the resultant form and to accommodate the three-dimensional rotation of scissors plates. Unlike other groups, this group of students relied heavily on physical models to complement their digital simulations. Students felt that the tactile qualities of physical models gave them valuable feedback about the levels of friction within joints and material resistance. Particularly in the situations when digital models became over-constrained and locked themselves in a particular position, physical models, due to their imprecision, gave a better indication of the overall assembly behaviour.

4. Rethinking Theo Jansen's Models

Inspired by Theo Jansen's kinetic sculptures, students investigated the design possibilities of a parametrically defined adaptive structure that mimics skeletal systems found in nature. They started by creating an exact replica, both physical and digital, of Jansen's Strandbeest kinetic mechanism. Then, with parametric models, they looked at how specific component dimensions and radii impact the

kinetic behaviour of the entire system. Parametric definitions allowed for fluid changes to a digital model and for immediate feedback on its kinetic behaviour. This helped students to understand the role individual elements played within the entire assembly and the types of motions these elements were capable to produce. These explorations led students to propose and develop an adaptable vertically climbing mechanism that used core principles of Jansen's models with changes to the types of constraints and possible motions.

Kinetic designs such as Jansen's sculptures that mimic walking structures, or Hoberman's expanding dome, require close and detailed understanding of kinetic mechanisms developed over time with multiple prototypes. Similar developments would not be easily achieved within a semester-long three-credit course. To short-cut the discovery process, students started with an already established design, in this case Jansen's walking mechanism, and investigated ways the logic for this particular mechanism can be extended to other forms of movement. While a physical prototype was an ultimate goal for the project, it was easier to experiment with variations of the base mechanism using digital modelling. However, conventional three-dimensional modelling software would not be an effective environment for prototyping. What was required for this particular project was parametric software that would deal with constraints and be able to pass them between various components. Revit (parametric BIM) and Grasshopper (graphical algorithm editor for Rhino) were suitable software environments for this project.

5. Kinetic Wings

Inspired by Santiago Calatrava's sunshade mechanism, the project (Figure 2) looks into providing a kinetic canopy with expressive wave movement. Students developed a number of prototypes, originally using Rhino software, and later physically building scaled-down models while testing various materials. Student testimonies below explain the development process along with the technical issues they faced: "While putting this model together, we realized that the acrylic pieces were not strong enough to resist the turning motion that was being applied to them. Parts began to fall apart. To solve this problem we had to remove one wing to lighten the weight and cut the larger openings in other wings without reducing rigidity."

Learning from the first model, students developed a second prototype "*that…is smaller in scale and is composed of different materials. The reason we did it was that the first model was made of acrylic which was more fragile compared to the originally intended wood. The bending effect happening to the acrylic was preventing it from moving the way that it should.*"

What students also discovered, and what is not evident from the above testimony, is that material substitutions may not always work unless the overall design

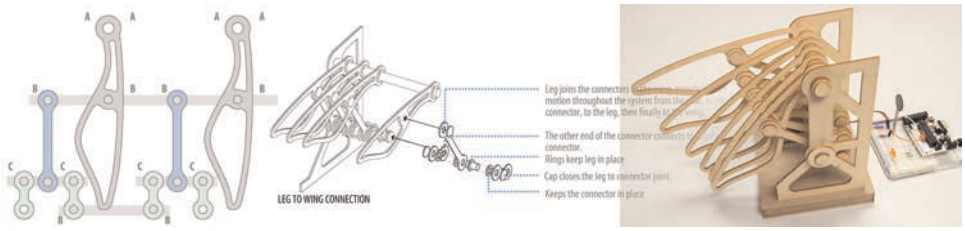

Figure 2. Façade screen digital and physical mock-ups.

or the design of individual components is appropriately adjusted. For example, a substitution from wood to acrylic may require changing the thickness of elements or redesigning their profiles to increase rigidity. Similarly, the impact on the friction associated with the component rotation should be considered.

6. Umbrellas

Another kinetic project used an umbrella mechanism as a departure point for adaptive structure. Starting by recreating an umbrella mechanism using the Revit software, students linked individual assembly components with explicitly geometric relationships (trigonometric functions/expressions). Students focused on developing design alternatives to the basic mechanism that investigated different forms of hinging of components and folding of the overall design. Part of the design and production focus went into mechanical controls of the mock-up with an Arduino microcontroller and sensors, in a similar way as the canopy project mentioned earlier did. In this case, the aperture of the umbrella was correlated with the light sensors positioned immediately below it.

Both projects, the canopy and the umbrella, used a simple mechanical precedent as the initial idea for the kinetic assemblies. While the final designs did not substantially redefine the initial prototypes, they were valuable learning experiences. They taught students the intricacies of kinetic architectural assemblies that predominantly rely on simple ball joints or hinge-like mechanisms. They also allowed students to re-examine the purpose of kinetic structures and tie them in with a broader conceptual framework of adaptive designs and intelligent buildings. Furthermore, by laying out the framework for microcontroller operability – if-else conditional statements – they were able to define a series of functional responses to a single parameter input.

7. Pneumatic Doughnuts

While a mock-up as a partial full-size prototype can be easily achieved with kinetic structures by building a portion of the overall design, with pneumatic

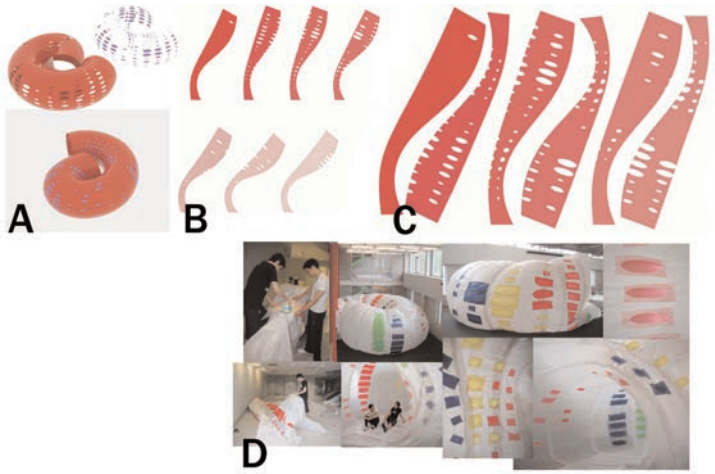

Figure 3. Pneumatic structure digital explorations and physical mock-ups.

(air-supported) designs a partial mock-up may not be as effective. One needs a critical mass of the "building" to have both structural integrity and air tightness. This limitation resulted in pneumatic mock-ups encompassing almost the entire design scope. The "doughnut" in Figure 3 (A and D) is an example of a pneumatic structure developed by students that went from a partial analysis and a mock-up into a full-blown prototype. Students envisioned it as a free-standing pavilion able to accommodate human activities in an unrestricted and comfortable way. The motivation behind the centrally organized form of a doughnut was to create a space that could be explored and also would allow for congregation. It appeared during the initial small-scale model experimentations that the overly linear space would provide the difficulty of uniformly inflating it, particularly if one were to rely on a single point, or not more than two points, of air supply.

Students started their project by developing initial three-dimensional geometry in Rhino software and fine-tuning its form, considering what a pneumatic structure would most likely look like.[3] Then they used the Kangaroo plug-in for Rhino and Grasshopper to simulate the physical behaviour of initial designs. During simulations, geometries with individual mesh cells were adaptively refined until an optimized form was achieved. Since the original Rhino mesh was an inert geometry (poly mesh) without any parametric controls, the resulting Kangaroo simulation was not as effective from a design point of view as compared to a parametrically controlled mesh that could be interactively changed during simulation. For this reason, students moved from the Rhino inert mesh approach to Grasshopper's parametric surface modelling environment and were able to explore a wide range

of design alternatives. In addition to interactive manipulation of the three-dimensional model, students were also able to control the levels of pressure and spring values to analyse the amount of inflation and impact on design.

While physical mock-ups are an ultimate proof of concept, they narrow a range of observations into a particular case study, tying them to a singular physical instance. On the other hand, parametric geometry simulations gave students an insight into a broader range of forms and their behaviours. It was often mesmerizing to watch how a particular design evolves over time, sometimes locking itself in a particular position or falling into itself (by folding) and effectively over-constraining itself, showing bifurcating scenarios for the form optimization. Adding more air pressure or changing spring net properties in most cases would not reverse tectonic outcomes.

As part of the mock-up explorations, students investigated several cut-and-unroll scenarios to find the most effective (tileable) sections (Figure 3B) to optimize material usage and minimize waste. The material economy became an important feature for the optimized final design. Available software did not allow for the direct material optimization that would help to find the zero-waste solution. For this reason, students had to study it in a recursive, indirect way by developing alternative unrolled sections and comparing them side-by-side to derive the most efficient approach. (Figure 3C)

8. Discussion

While tensile and pneumatic mock-ups were full-size deployment of partial structures, the kinetic assemblies in most cases were scaled-down versions of original designs. The reason for this approach was to reduce material and power requirements for the kinetic components. In the case of mechanically powered assemblies, this allowed for the use of servos and small low-voltage motors instead of full-size high-voltage electrical motors. It also allowed for the simplified production of the mock-ups, since most of the components were produced with laser cutters. Even though the kinetic designs done by students were reduced-size models, they were effective tools to evaluate kinetic structures. However, the same approach would not work with the tensile or pneumatic assemblies, since in these cases the material properties and acting forces could not be easily scaled down while exhibiting the same structural behaviours.

The exploration of pneumatic and tensile structure not only gives students the ability to simulate structural behaviour and derive unique forms but also helps to explain the principles and science behind calculations. In the case of tensile and pneumatic structures, quad-based surface meshes, familiar to students from three-dimensional modelling software, are used as “virtual” spring nets (exemplifying Hooke’s laws) to simulate tensile behaviour and derive optimized surfaces.

In these spring-net models, mesh edges are interpreted as springs, while vertexes are points where forces such as gravity are applied. The displacement of vertexes is controlled by a spring's ability to expand, the tendency to return to its resting position, and the amount of physical force (load) applied to individual points. Once all loads and spring properties are defined, the surface is going through self-normalizing reiterations and ultimately settles down in the optimized target tension state. By controlling the initial and the resting spring (edge) lengths, we can simulate both stretching and contracting surfaces. This approach can be used effectively for tensile structures as well as for geometries that wrap around a group of objects and produce a surface with a minimum volume.

9. What is Being Learned from Digital Versus Physical Mock-ups?

With today's generation of students, who often have a better grasp of digital than of physical tools, the requirement to manually construct designs is probably even more important than in the past. Since the architectural profession ultimately deals with physically constructed buildings, there is a need for students to understand the translation process of their ideas from the digital to the physical. I have observed with many students the perception that once design is modelled in a three-dimensional virtual environment, it is perceived as fully resolved. If it can exist in a three-dimensional model, it also has the right to exist in a physical setting. While this may be true from the geometrical point of view, as compared to traditional two-dimensional representation of buildings where different drawings did not have to be reconciled spatially, it is not true in other aspects of design. The present computational tools solve some of these issues but still leave many of them unresolved. Specifically, material properties, physical behaviour, and contractibility continue to remain unaccounted for in most software packages. While the approach discussed above points to ways of addressing the issues of material properties and physical behaviour, physical mock-ups prove to be an effective learning environment. By constructing kinetic designs or pneumatic structures, students experience the intricacies of mechanical assemblies and material limitations. The geometric precision taken for granted with software packages becomes a major issue when manually constructing kinetic designs. Centre of gravity and points of rotation are important factors in the effective operation of kinetic assemblies. The process of building and rebuilding mock-ups, discovering imprecision in produced work, facilitates the discussion on types of loads (concentric versus eccentric) and moments associated with them. Students experience firsthand the need for design tolerances and the ways they can be incorporated in their designs. Overall, students moved away from idealized computer-based reasoning toward more holistic thinking about a building as a probabilistic structure – a result of compounding imperfections and tolerances.

Similarly, material choices become critical when considering both types of structures, pneumatic and kinetic. In pneumatic designs, the weight of the material had to be offset by the applied pressure and the quality of seam welds. Designs had to strike a fine balance between a membrane (skin) and the underlying skeleton, particularly in the air-inflated pneumatic structures that are supported by pressurized air within an inflated structural core. In the kinetic designs, the material-to-material interactions – friction – and fatigue become critical design drivers. Repetitive movements, rotational and lateral, quickly affect the material integrity and connections when applied for a longer period of time. This became evident in a number of projects that used wood-on-wood assemblies, where even a change in the air humidity would affect component movements. While most of the mock-ups were realized with hand tools and traditional woodshop machinery, kinetic designs had to resort to laser cutting of the individual components. This in turn predefined the range of possible materials, with acrylic glass being the most effective from the standpoint of material durability and appearance.

10. Summary

While each case study project tackled a particular structural system with its own, often narrow, characteristics and concerns, as a group students dealt with a number of important design issues that start to permeate into everyday architectural practices. Considerations of efficient material usage, or designing for kinetic and adaptive structures, are just examples of challenges and opportunities associated with current practices. Probably the most important lesson came from the student hands-on involvement in creating-making their own designs. It is rare in the course of architectural education that students have an opportunity to test and realize their own creative ideas, albeit in an abbreviated mock-up-sized magnitude. The built mock-ups in most cases differed from the original ideas. While building them, students went through a give-and-take process of negotiating initial design aspirations against material and structural considerations. This back-and-forth process, culminating with building a physical mock-up, provided students with an important feedback mechanism regarding their often digitally idealized creative thinking. I found that building physical and digital mock-ups, and reconciling emerging differences, effectively situated design challenges and provided vehicles for their resolution.

Endnotes

1. As evident in Filippo Brunelleschi's work, among others.
2. One of the areas where physics-based form finding is used in architecture is in the design of tensile structures such as tents and cable nets as well as pneumatic struc-tures. Small-scale models using canvas, chains (Antoni Gaudí), and soap films (Frei Otto) have been used to derive these

surfaces, since they approximate minimal-tension surfaces. However, measurements and controls of these models can be difficult, in addition to material and scale differences that make any measurements only partially useful.

3. The reason for "pre-cooking" the simulation – starting with the geometry that is close to a final pneumatic model – was to minimize time and avoid simulation artefacts. In some cases when optimizing more extreme shapes, such as a highly wrinkled form, even after a relatively long simulation time there were still residual elements of the original wrinkles in a simulated geometry.

References

Ambrose, M.: 2009, Agent Provocateur – BIM and the Design Studio: Questioning Roles of Abstraction and Simulation in Design Education, *in* P. Crisman and M. Gillem (eds.), *The Value of Design*, ACSA, New York, 85.

Otto, F. and Rasch, B.: 2001, *Finding Form: Towards an Architecture of the Minimal*, Axel Menges.

Hannu, P.: 2007, Early Architectural Design and BIM, *in* A. Dong, A. Vande Moere and J. S. Gero (eds.), *Proceedings of the CAADFutures'07*, Springer, 291–302.

Wallick, K and Zaretsky, M.: 2009, Fragmentation and Interrogation as an Approach to Integration, *in* P. Crisman and M. Gillem (eds.), *The Value of Design*, ACSA, New York.

Zarzycki, A.: 2009, Dynamics-based tools: an unusual path to design integration, *Proceedings of the ACM SIGGRAPH ASIA 2009 Educators Program*, ACM, New York.

Zarzycki, A.: 2011, Form-making Without Form Making, *Proceedings of the Parametricism (SPC) ACADIA Regional 2011 Conference*, Lincoln, NE.

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MOBILIZED MATERIALS

Textile Constructs

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Abstract. This paper investigates textiles techniques and their potential for creating ornamental and structural systems investigated through a sequence of design studios. Within the paper 3 examples of textile systems are introduced that range from a Semperian approach (wall as dress) to form finding experiments with active textile materials (Frei Otto).

Keywords. Textiles; form-finding; analogue computing; design methodology; craft.

1. Introduction

All materials, when sufficiently mobilized, find ways to organize themselves. In human crafts we find similar ways to create patterns, as long as the materials are allowed to be flexible and to configure step by step into a final shape. The research focuses on textile techniques and uses analogue computing or "Formfindung" to mobilize the materials. Materials are allowed a certain amount of freedom to act as agents and process forces in order to configure into a more structural state. The term "analogue computing" is linked to Frei Otto's experiments on form finding and Gaudi's catenary techniques, but can also be applied to Semper's Stoffwechselthese, where one material system informs another.

2. Methodology

The methodology of the studios is based on a systematic procedure that Lars Spuybroek has developed and documented in the R+D series (Spuybroek, 2009; Spuybroek, 2011; Baerlecken and Riether, 2012). He adapted his design

methodology to fit within the frame work of a second year studio and coordinated the presented design studios that proceed in three phases:

- Phase I: All patterns systems have figures that configure into more complex configurations. Pattern systems are studied through material studies. The configurations lead to vertically hanging or standing "nets", two-dimensional systems that have ornamental surface qualities as well as structural qualities.
- Phase II: The flat nets are thickened or multiplied. More complex operations such as peeling or small distortions are explored.
- Phase III: The spatial and structural effects are studied and developed. Circulation, routing, lighting, etc. are developed.

The materials used for this exploration start with flexible threads (from yarn to plastic tubes to wood fibers), but transition then to flexible strips (from paper to cardboard to wood) or to rigid sticks (wood) or to flexible surfaces (from rubber, to textile to paper).

Materials are subsequently researched within the realm of certain techniques. Some techniques will fit exactly with the proposed material (weaving with thread), others less, and some not at all (weaving with rigid sticks) – this is intended to introduce the problem of transferring the diagram to architectural materials.

3. Performative Ornament

In order to understand which outcomes of this procedure are desired, we want to look at the role of ornamentation. Following Kant (1790) ornament is defined with a negative connotation as parergon, as an addition, as supplement, as decoration, as applique, as accident in contrast to the ergon or substance. Ornamentation becomes synonymous with veiling and hiding. Ornament is extrinsic and hides the Ding an sich, the thing-in-itself, the substance. Kant gives us three examples, where real beauty suffers from ornament: cloths that cover the naked body in sculptural decoration, decorative columns of classical architecture, and the frame of the paintings.

Through Derrida in the Truth in Painting, we know that Kant's degradation of ornament is based on the clear distinction between intrinsic and extrinsic. Critiquing Kant Derrida (1987) asks:

> "What about the frame framing a painting representing a building surrounded by columns, columns in the form of clothed human bodies?"

He demonstrates that there is an in-between state: the parerga operates separately from the ergon, but is at the same time not entirely extrinsic to it.

The research focuses on these in-betweens or folds, as Derrida also calls them. We are not following a modernist logic of separation and differentiation of parts, but try to generate systems that integrate a variety of parts with multiple functions

into one system, as one can observe in natural systems (Weinstock, 2010). For example a certain pattern performs as ornament, structure and shading devise.

Within the process of transferring a textile system to architecture through the introduction of different materials (from soft to rigid) this approach tries to foster integration of systems, which have been separated in Modernist architecture.

There are two groups of techniques. The first group has more precisely described techniques where existing figuration (the type of loop, knot or interconnection) lead to specific patterns: lacework, macramé, plaiting, knitting, weaving, plaiting, and braiding.

The second group offers a more abstract sense of techniques, where individually distinct figurations have to be invented leading to specific configurations: felting, pleating, interlacing, figuring, combing, and wettening.

In the following three paragraphs we are discussing three examples, each a different technique, demonstrating the process of material computation and their transference to another material system in connection with digital tools. All presented techniques create patterns that perform as ornament and structure. But the three different examples vary in their emphasis of these two aspects. The first example focuses on dressing (Semper), second example studies figuring as a technique that equally balances ornament and structure (Gothic), and the last group foregrounds structure (Frei Otto). But there is always an ornamental and structural component present in all three examples.

4. Technique 1: Dressing

In order to understand the importance of Semper for this research procedure, we have to look at two theories developed by him: his theory of dressing (Bekleidungstheorie) and his Stoffwechselthese.

During the Crystal Palace exhibition (1851) Semper sees a Caribbean hut, which reinforces his theory of the Four Elements. As a counterthesis to Laugier's primitive hut Semper formulates a model of four fundamental types: the earthwork (masonry), wooden frame (carpentry), the textile membrane (textile) and the hearth (ceramics, metal). Challenging Laugier Semper emphasised the textile membrane through his "theory of dressing" (Bekleidungstheorie), which makes the aesthetic performance of the wall through ornamentation more important than its structural performance. For Semper architecture has its origins in textiles, in weaving, and in braiding, through the light and highly ornate nomad tent architecture. Subsequently Semper contrasts two types of enclosure: (a) die "Mauer" and (b) "die Wand". Both translate as wall into English. In German there is an etymological difference between the two words. "Mauer" is a construct that is put together through masonry (mauern = to lay bricks), whereas Wand refers to

"winden" (to twist, to wind) as a construct that is assembled through bending, winding, twisting thin, bendable, soft twigs. The "Mauer" is a fortified, solid, monolithic wall serving to create security. In German "Wand" can be linked etymologically to Ge-wand, dress. So the "wand" is a type of enclosure that is a light textile carpet in the likeness of a screen-like wicker work or an ornate dress. The fortified wall provides security and structure whereas the wall-carpet creates spatial enclosure. The two can exist in direct relation to each other (medieval castles/tapestry) or in loose relationships.

The second Semperian theory, the Stoffwechselthese, is highlighted in our work. Stoffwechselthese is sometimes translated with metabolism thesis, but could be read as Stoff- (stuff/matter/material) –wechsel (change/transformation)-thesis. One material is exchanged through another. We see a technique where one material is transferred to another substance in Semper's example of the textile transferred through stone carving. Semper sees this theory proven by the translation of textile motifs into the polychromatic dress of Greek temples.

Figure 1 and 2 show two examples of textiles techniques that transform through a change of material process. Figure 1 shows lace as a textile technique.

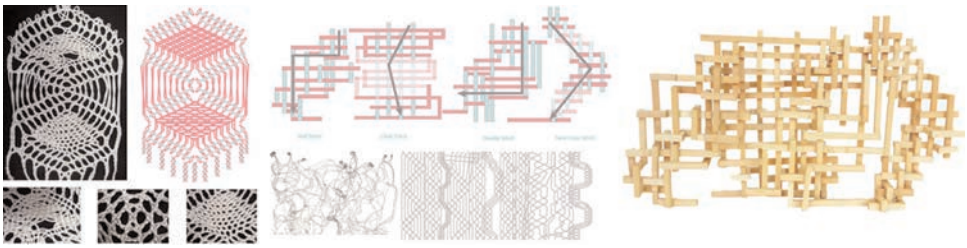

Figure 1. Lace configuration and their transference to a linear, rigid material system.

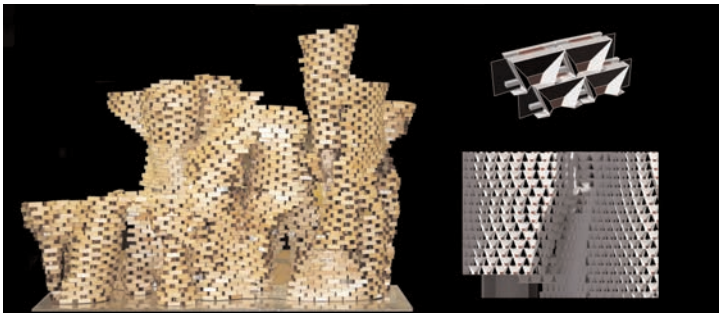

Figure 2. Knitting with wooden blocks (left) and digital model based on a loop stitch (right).

In phase 1 different lace types are studied such as: needle lace, bobbin lace, knotted lace, knitted lace, crochet lace, etc. In this first phase the technique is studied through a textile material/thread. The focus lies upon understanding the complexity of pattern making linked to the techniques applied. In next step the material changes: thread is replaced with bendable wire and rigid sticks. The study of bendable wire is less successful, since it introduces unintended deformation of the pattern and does not increase the rigidity of the wall system significantly. The study with rigid sticks is far more successful, since the wall becomes structural and the pattern maintains its complexity, but the lace pattern also changes its properties through the introduction of the new material. In a Semperian sense Stoffwechsel is taking place, as the lace informs the wood and the wood sends information back to the pattern. The rigid wooden sticks allow for certain operations to be performed as in the lacework (loops with larger radii), but edits out operations that cannot be performed with a rigid element (loops are no longer curvilinear and the dimensions of the material dictate the intricacy of the pattern).

Figure 2 shows a study of knitting. Knitting is a technique that uses yarn to create consecutive rows of loops, which secure each other in the process of making. After the initial phase that studied a series of techniques with different stitches which allow the creation of different textures (such as warp knitting, knit and purl stitches, cable stitches), the study focused on different surfaces types in order to increase structural properties of the system and to create spatial enclosure: from flat surfaces over twisted surfaces and single curved, open surface to enclosed cylindrical surfaces. Figure 2 shows the process of transferring the knitted surface to a structure made from blocks. The ability of a knitted surface to create different spatial and structural wall types informs the making of a block-based model. Again, two material systems communicate bi-directionally. The digital model in figure 2 shows how a precast concrete block could be developed by reading, in this case, information from a single-loop knitting pattern.

5. Technique 2: Figuring

The ornamental and structural qualities of figuring are best illustrated in the work of Gothic architecture. Gothic architecture combines ornament as tracery characterized by a rhythmic organization, and a system of geometric construction following a structural logic. The configuration of curvilinear figures is informed through a material. The change of material produces variation in the lightness of the structure: stones (Chartres), brick (les Jacobins) or metal (Labrouste). The translation of one material into another in these examples reflects an increase in “structural lightness” which follows the same structural systemacy: bundled columns transfer into ribbed vaults creating ribbon surfaces. The gothic wall is

very close to a Semperian textile “wand”: the gothic wall synthesises both Semperian wall types into a structural wall carpet.

In modern architecture the structure is detached from the wall - the post and slab structure of the Domino frame. The curtain wall has replaced the wall-veil; the maximized “lightness” of the curtain is achieved. However, the curtain wall has lost the ability to form complex configurations, and remains dependent on separate structural systems.

We respond by studying the construction of structural surfaces through active figures (Spuybroek, 2011). The following example employs figuring as a generative system to creates structural surfaces. Figuring is a technique that follows the methodology of gothic structures that use I-, J-, S-, and C-figures. In the chapter titled, “The Digital Nature of Gothic” (Spuybroek, 2011, p. 20) Spuybroek argues, per Ruskin’s description of gothic, that ribs are the elements of constant variation and in order “to keep getting new configuration, one needs both different figures and different combinations of figures”. “Figuring” within the basis of gothic design allows a new form of rigid structure that can free itself from the rules of earlier gothic systems, which only work in compression. The evolution of flat surfaces to three-dimensional structural surfaces results from specific transformations such as shifting, pinching, or warping.

Figure 3 show a figuring project, which develops a structural façade attached to an existing building. The project starts by defining the minimal set of figures that can produce the maximum configurations. Variations are a matter of size/scale and diversity of curve. The challenge is to create a system of line work that is continuous and can perform at different levels. The figures once transferred to rigid material can become structure, ornament, screen, or window.

The design is based on a set of figures generated by the offsets of a circle to create nested figures with relationships of 1 to 1 or 1 to 2. Straight and curved ver-

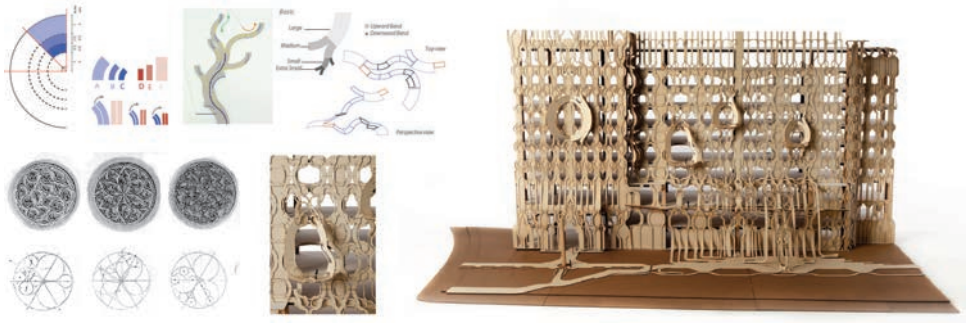

Figure 3. Figuring.

sions of each type produce a total set of 6 figures. The figuring process builds up complexity through the controlled variability of configurations, arrangements, and scale. Scale and arrangement breed the hierarchy within the technique's system. Using the individual parts, the project explores creating a series of similar figures that begin to interlock with each other. Methods of reflection and translation are used to create a repeatable pattern that can continuously expand. As developed patterns are repeated and connected, variations are introduced to the original movements, allowing for a flexible and adjustable system for growth. The pattern then reacts to its environment through variation. The surface achieves three-dimensionality in two ways: by duplication and rotation of elements, and by bending elements inwards and outwards. The deformation generated by the last technique is palliated by insertion of more figures to reinforce the structure.

In phase 2 the project proposes a structural skin with solar-responsive cladding elements. Using figural variations, the skin performs in high visual density and almost complete obscurity, as well as open and porous conditions, which act as "windows" where desired. The skin changes with each face, with small apertures and built-in shades on the South and West sides, and large apertures on the East and North sides. In some cases the skin presses outwards into a two-layer system. The elements are designed to be precast concrete, mounted to the existing frame by a direct-to-slab anchor. The skin performs the two main functions as noted above and proposes responding to solar radiation on the site. The figures relate to human scale in what is otherwise a larger-than-life proportional system.

6. Technique 3: Analogue Computation

In the early 1990's Frei Otto and the Institute for Lightweight Structures in Stuttgart investigated what they termed "optimized path systems". Material machines were devised to test complex material behaviour, reorganizing the system by introducing one material with another, creating a transformation of the material system. The organization of matter through a material machine process involved the use of liquids and solids, where material began as liquid and ended as rigid. (Spuybroek, 2011) These material machines restructure themselves through interactions among elements in a restricted time, and the material "finds [a] form". The material forces by transformation, computes these interactions, and resolves in a geometry that is derived from a complex material behaviour. This is a form of analogue computation. These textile machines generate complex structures as they transform from their wettened state to their rigid form. Otto explored the potential of a material machine to restructure a system of dry wool threads by dipping them in water. Bound at determined ends, the wool threads are free to bind to one another, creating a new flexible network, which varies with each dip, as agents are free to restructure. (Figure 4)

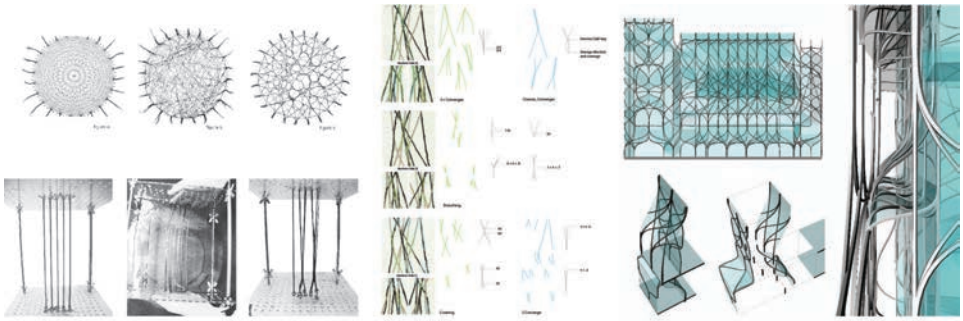

Figure 4. Wettening configurations and their transference into a structural façade system.

Wettening is a technique used to configure flexible elements (ex. wool thread) through sticking. In one study students explored wettening as a method to compute an architectural structure. A material machine is made by dipping a matrix of wool threads, which are suspended between two acrylic plates with fasteners into a pool of water. A variety of thread relationships and slacks are tested with each dip and the threads compute structural relationships with one another. (Figure 4) The number of paths is minimized, sharing geometries of merging and bifurcating, much like a vectorized system.

As seen in Figure 5, the felting technique defines the nesting of loose fibers or strips into a surface or volume. The study explored agitating paper strips, behaving as fibers would in a glue and water liquid for several seconds as new strips are added periodically. A screen is lifted through the liquid, straining the paper strips through the liquid mixture. The nested strips become hardened and fixed, creating

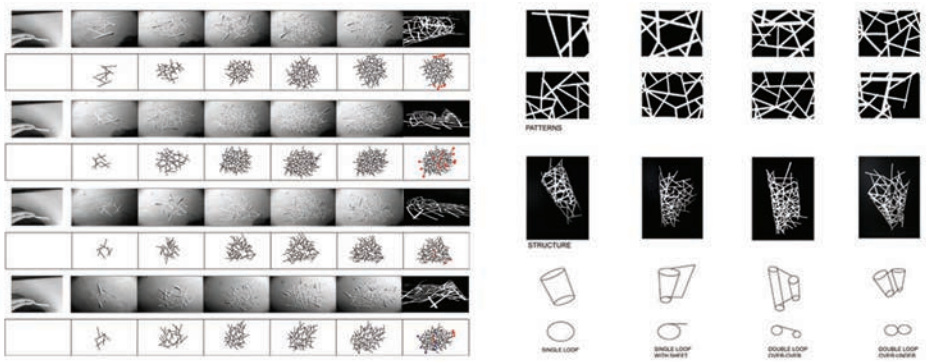

Figure 5. Felting patterns and their transference into a rigid structural system.

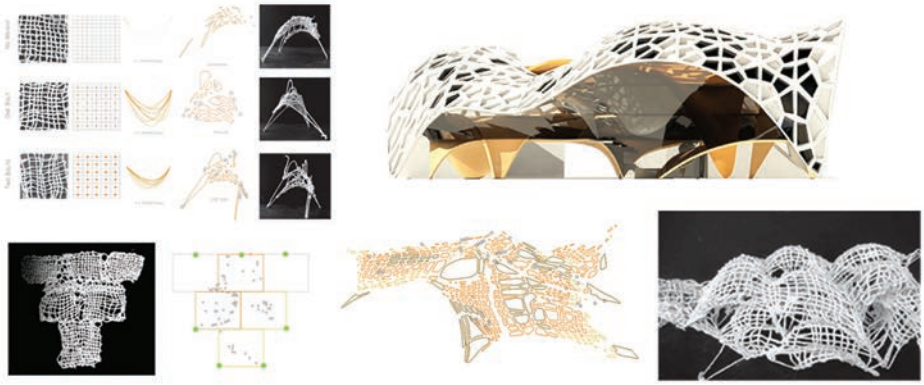

Figure 6. Weaving plaster dipped machine and catenary curves.

a static patterned net. The pattern's variation in density and area is dependent on the duration of the machine's agitation. The pattern's surface is folded and nested vertically to create cylindrical vertical volumes.

Weaving is a technique that works from a loom with elements fixed in one direction. The computing machine for this study (Figure 6) blended two analogue computing techniques. The first, like the wettening study, dips a network of fibers softly structured in a rectilinear swatch of a woven pattern into a water and plaster solution. The soft structure is coated by the solution, creating additional weight and freedom for movement. After the dip the soft structures are hung upside down from a horizontally braced frame. The weight of the solution and with the addition of weights creating force and movement to a soft flexible material system. These soft structures behave much like Gaudi's inverted net study where a structural system of catenary curvatures calculated for projects like La Sagrada Familia in Barcelona, Spain. After the initial analogue experimentation digital tools allowed students to develop a building that explores multiple structural shells in connection with programmatic and contextual forces.

In these studies the use of digital tools became necessary in developing the project. Students moved between software applications, utilizing the digital computational tools to advance the precision of the project.

7. Discussion

The methodology has been productive in creating ornamental and structural wall systems. The material transference from yarn to another material has allowed the study of architectural problems. Nonetheless, future research could foreground

tectonic aspects linked to construction through the construction of large-scale mock-ups.

Acknowledgements

Figure 1 and 2 show the lace project from Sol Kim and Songmi Kim, figure 3 the figuring project from David Varner and Morgan Strickland, figure 4 the wettening project by Catherine Quigly, figure 5 the felting project by Kelsey Hollington and figure 6 the weaving project by Jennifer Blyth and Stephanie Douthitt.

References

Baerlecken, D. and Riether, G.: 2012, *Aggregates: Digital design for design 1*, *Proceedings of CAADRIA 2012*, 607–616.

Derrida, J.: 1987, *The Truth in Painting*, Trans Geoff Bennington, CUP, Chicago.

Kant, I.: 1964, *The Critique of Judgement,* Clarendon Press, Oxford.

Otto, F. and Rasch, B.: 1995, *Finding Form : Towards an Architecture of the Minimal*, Axel Menges, Germany.

Spuybroek, L.(ed): 2011, *Research & Design: Textile Tectonics*, NAI Publishers, Rotterdam.

Spuybroek, L. (ed): 2009, *Research & Design: The Architecture of Variation*, Thames and Hudson, London.

Weinstock, M.: 2010, *The Architecture of Emergence: The Evolution of Form in Nature and Civilisation*, John Wiley & Sons, Southern Gate, Chichester.

INTERACTIVE AND PARTICIPATORY DESIGN

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GENERATIVE DESIGN INTERVENTION

Creating a computational platform for sensing space

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Abstract. This paper outlines some investigations from a project which utilizes computing and scripting of specific site components, spatio-temporal movement and behavioural patterns to explore how designer might understand people activities and formulate design interventions within public spaces. This research looks at how generative tools can facilitate designers to integrate the large volume of information received by hybrid data collection, and conventional data analysis directly into the design process. Through an examination of sensing urban space, this research proposes a method to track and record people's movement patterns in order to implement them via generative design tool. To facilitate this, a scripting method is specified; which uses sensors and motion tracking devices to capture the use of a specific public space. This project proposes a methodology for developing designed spaces and optimal pathways generated from real-time data and feedback captured by sensors.

Keywords. Real-time computation; generative design; sensing space; design simulation.

1. Introduction

The complexity which forms the 'hidden dimension' of people in public spaces has been noted by theorists such as Edward Hall (1966). Those dimensions are important to understand how people use urban space and move in it. Sensing space can give designers a lot of information regarding people activities, however, the challenge for designers is to consider, and actively respond to the data that is captured by conventional analysis and sensing technologies in design processes. This paper suggests a system to create meaningful design decisions by processing the captured data in a generative design tool.

The implementation of generative methods in digital design has produced intangible outcomes; the design produced, using these methods, is not linked to people activities in a specific urban environment. By using generative tools, designers are able to create interesting aesthetic shapes, simulate environmental conditions, and/or illustrate people movements. However, such use of generative methods has not solved a connection between the data gained by site analysis and design process. This research creates an outline of how generative tools can be linked to tangible parameters which will be processed to solve urban problems.

Designers are not equipped with the ability to simultaneously grasp, consider and implement the results of such rich data into design outcome (Alexander, 1964). By using data storing algorithms and feeding the culled data to a generative tool, designers will be able to isolate and directly include relevant data gathered by hybrid and conventional methods into their designs.

This paper outlines a method for sensing space and recording information from public spaces using motion tracking sensors. It demonstrates, through a case study, how the captured data can directly inform generative design tools, and establish feedback loop. Utilizing Processing programming language, this aims at recognizing and recording the use of movement patterns in public space, and forming parameters which are transferred into Rhino and Grasshopper for design generation, thus allowing the development of architectural threads to create new public nodes and alternative connections between new and existing site nodes in three dimensions. This research suggests a way to test and improve public spaces by capturing the use of those urban hubs.

2. Background

The development of digital tools and design scripting has informed architecture and stimulated a paradigm shift in which a new language of generative form creation has emerged (Heinich and Eidner, 2009). Scripting platforms as Processing and C# have become available for designers, such platforms made it easier for them to generate their own complex scripts (Reas and Fry, 2007). These tools have thus far neglected people. Algorithms utilized here are yet to properly address the relationship between people and the surrounding environment within a proposed generative design system. Generative tools, in this research, have the potential to utilize information gathered from a site, and assist designers to create designs that will better acknowledge and respond to how people use public space (Figure 1).

Recent initiatives in real time tracking of people's positions using aggregate records, collected from communication networks, can expose movement patterns. Those methods provide means for understanding the present use of space and anticipate future patterns of urban movement (Calabrese et al., 2011). However,

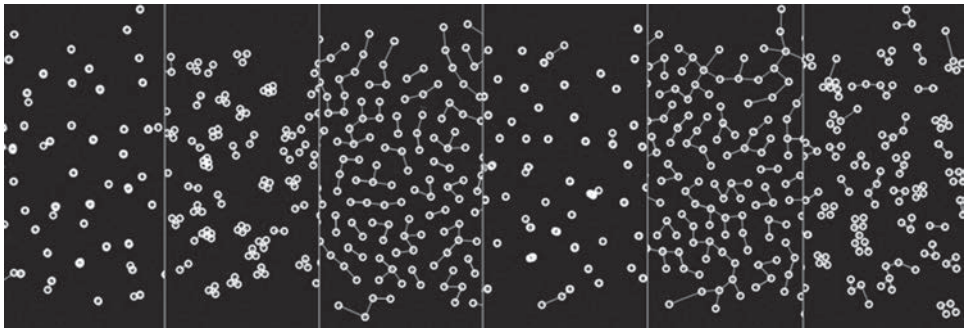

Figure 1. Intimacy – a Processing sketch – still images shows initial study of particle relationships to define the study parameters.

such analytical methods have rarely been used in digital design tools; this may prevent many designers to easily test their design in the virtual environment.

Most of the work that has been done with generative scripting, which looks like the swarm behaviour, was to simulate the movement of people in space or to create aesthetic illustrations. If the moving particles were driven by realistic data from a specific site, a designer can develop an understanding of how people will use that space, furthermore, she/he can use this script to test her/his design outcome before applying it. This method will help urban designers predict activities and movements in the future by understanding the behaviour of people in present time.

3. Problem Definition

In order to test the tools created as part of this research project, the digital scripts have been applied to a case study site in Hong Kong.

As one of the most densely populated cities in the world, Hong Kong has developed unique conditions of public space and is characterized as a forest of high-rise cul de sac towers (Shelton et al., 2011). The tested site is a transportation hub, directly adjacent to an aging hybrid development; the Shun Tak Centre and the Hong Kong-Macau Ferry Terminal and Heliport.

Much publicly accessible space in Hong Kong is not available as a true civic space, due to it is being privately owned and security surveillance discourages relaxed social gathering from occurring. There is however, a strong history of a fluid mixing of public and private space in Hong Kong, and extraordinary examples of transformative spaces which accommodate huge shifts in the uses of public spaces. A notable example is the way the HSBC headquarters ground level is given over for use as essentially private space to the Filipino maids on Sundays. It is this

changeable space that has motivated the investigation of a method of sensing space which demonstrates patterns of space utilization.

The project aims to identify principles which could define volumetric public spaces through the coding of connections, pathways, and people's movement within the site. Furthermore, it will redefine the connections between the site and the surrounding city. Data sensing was conducted using photo-recognition and motion tracking sensors, then sent to generative tools in Processing and Grasshopper.

4. Tool Design and Description

Recently, image recognition, image detection and people tracking technologies have been developed for game-based devices. Most of these techniques are used in architectural design as surveillance systems. For example these monitoring systems can be encapsulated by the development of intelligent buildings (Albrechtslund and Ryberg, 2011). Image recognition tools and techniques can also be applied in a specific site to track and test the overall patterns of people movement. Furthermore, 3D motion tracking methods can be applied to certain public spaces to analyse the relationships that exist between people utilizing the space. From these two techniques, we can isolate parameters such as distances between people and feed them to a generative tool. For this research, two methods of sensing space were utilized: Microsoft Kinect as a motion tracking sensor, and Time-lapse Image Processing. In addition, one generative tool is being developed to process data and create new nodes and pathways (Figure 2).

Digital video content analysis is an important part of visual surveillance systems. Some interesting programs have been developed which use generic object detection and/or tracking (D&T) algorithms such as; subtraction (BS), Continuously Adaptive Mean Shift (CMS), and Optical Flow (OF) (Karasulu and Korukoglu, 2011). However, these techniques are rarely used in urban analysis and design. Within this research project a component has been created in Grasshopper which can inform the generative tool. This algorithm can track people in any video or sequential images captures from a specific site and create parameters of people's locations and movements (Figure 3).

Gaming technology has produced devices that potentially have interesting design implications and experiments are currently conducted using devices such as Nintendo Wii console in 3D programs (Payne and Johnson, 2012). Specifically, Microsoft Kinect has been utilized due to its ability to allow users to be freed using sensing devices, by directly detecting bodily movement in three dimensions (Brennan et al., 2012). Using those tools will give good results for people's positions and the relationships between one to another. Furthermore, it gives the ability

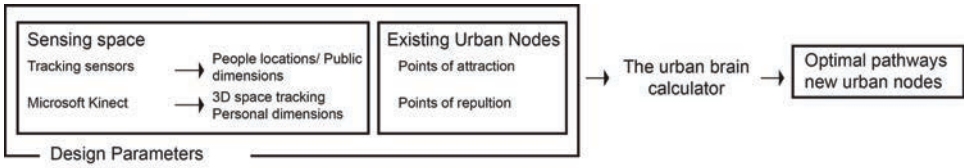

Figure 2. Study flowchart diagram.

Figure 3. Testing video inputs to record people movement using Quokka add-on in Grasshopper.

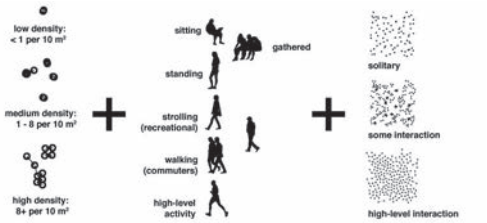

Figure 4. Diagram shows recording data into parameters.

to pin-point and track main joints of an individual and provides feedback as to whether the individual is standing, walking, or sitting.

Using the above two techniques (surveillance systems and Microsoft Kinect) has created rich data to be used as parameters for the algorithm developed in this research (Figure 4). By using Quokka add-on in Grasshopper (Brennan et al., 2012), all the work can be processed in nearly real-time. Furthermore, the data gained can be saved in an excel sheet file for future use.

The current research aims to develop the algorithm to store and process data, gathered from sensors, and simplify it to use as variables with which to feed the generative component. The generative tool establishes pathways in a 3D volumetric space (Figure 5). This space is limited by the constraints of a specific site. The tool will enable nodes to be identified as potential locations to form public spaces.

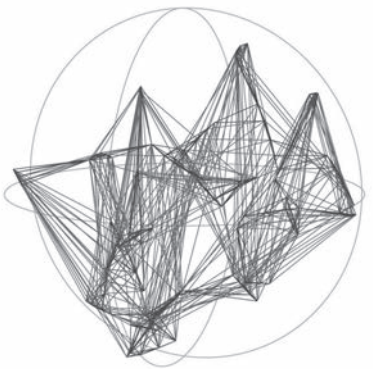

Figure 5. Testing the generative tool in a sphere.

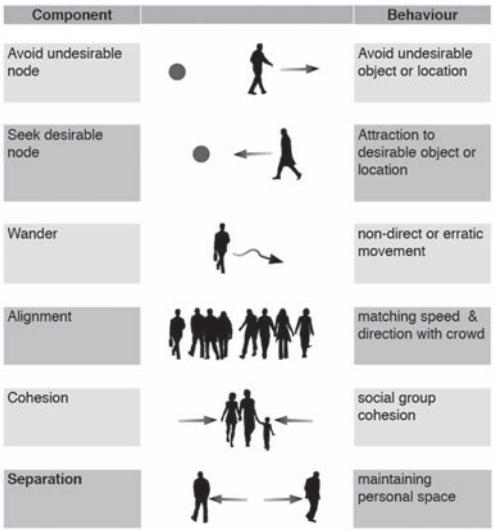

Figure 6. The generative tool principles:
a. define location of attraction, repulsion; b. use group of points (which represent people) as path generators; c. allow the points to move and respond to the tool parameters; d. focus on the pathways created; e. allow further movement and pathways to be created over time; f. addition of behaviours for movements.

In order to simplify the scope of the research, the code investigated two major relationships: the behavioural relationship between people moving in space, and points of avoidance and attraction (Figure 6).

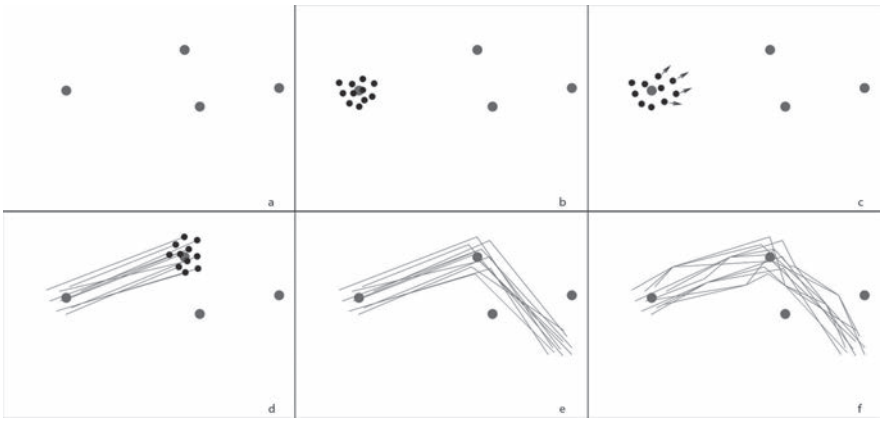

Figure 7. The generative tool behaviour diagram.

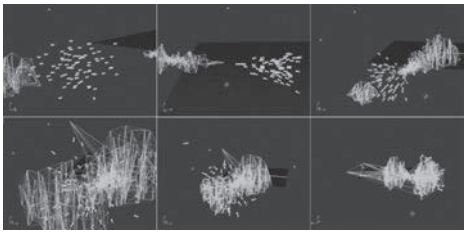

Figure 8. The urban brain calculator.

Some behavioural relationships in this experiment were: people's alignment as a public group, and cohesion and separation to represent personal space of individuals and groups. Within the urban context, two factors were considered to aid calculation of the optimal pathways/public spaces- in terms of volume and location: the distance to points of avoidance and attraction, and the location of those points (Figure 7). Whilst there is provision for further factors to be added to the algorithm, only the above mentioned proxemic relationships were analysed within this phase of the research.

The above parameters will be calculated in a C# script in Grasshopper, which has been named *The Urban Brain Calculator* (Figure 8).

5. The Urban Brain Calculator

Steering behaviours have been developed in gaming technologies to represent virtually the flocking behaviours of birds (Reynolds, 1999), these experiments have

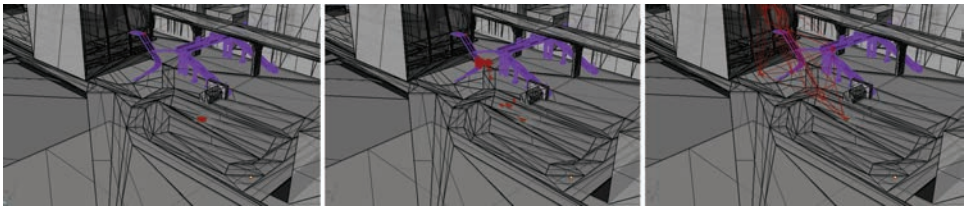

Figure 9. Testing the code on one node of the site: the connection between the pedestrian bridge and Shun Tak centre.

been further expanded for use in generative art and design applications (Pearson, 2011).

The Urban Brain Calculator runs in Grasshopper environment (in Rhino 3D) and calculates all the previous behaviours, that were captured from the sensors, and processes them to create pathways. The creation of the pathways depends on the notion of Proxemics (Hall, 1966), and therefore adding, time or duration of movement as another factor within the code.

Any designer can use the proposed script to test his design or create pathways that is driven by the available parameters described above. To use the script, you need to specify the important urban nodes in or around the site, the points that are not desirable, and the new proposed activities as points in Rhino. After running the script, she/he will be able to see the suggested pathway that will be created by the script in volume, furthermore she/he can assess her/his design by comparing the generative pathways with the design (Figure 9).

6. Outcome and On-going Experiments

The exploration of the outcomes based on behavioural relationships between people and the urban environment shows that experimental applications such as this are valid and can achieve interesting outcomes. The Hong Kong experiment has enriched the understanding of the volumetric calculations of personal and public space and the computation of generative tools as design statements. These statements may serve as multi-objective representations between people and public space.

This paper demonstrates how the application of such an approach enables the relationships between people who occupy a specific public space to be reconstructed and implemented within design process so that design that can include a multitude of decision making factors can be tested virtually.

The current script bring all of the parameters and use them equally, one development for this script is to define another parameters which can be factors

multiplied by the existing parameters in order to create more accurate results of translating people relationships in an urban space.

The research is still at an early stage; such sophisticated analytical and simulation techniques can provide sufficient set of design parameters. In carrying this work forward, more studies will be dedicated to different computational simulation strategies including agent based systems and more investigations of how to translate conventional urban design analysis into number based parameters.

The current work can help designer understand people relationships and desired locations in new environment, therefore a designer in Germany for example can create a design in China and test it using this tool. The tool will help him understand people behaviours which vary between cultures.

The testing of 'repulsive' and 'attractive' identifications is driven by parameters, therefore, the final round of images suggests a test of a specific area in the site, however, this paper doesn't claim that those images can formulate a completed design for that specific site. It is actually showing one of the possible outcomes by some assumptions as the script was tested and tweaked in that site for three days only. The research will give more accurate outcomes if the same object(s) is tested over the passage of time in a week and/or in a season.

Acknowledgements

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References

Albrechtslund, A. and Ryberg, T.: 2011, Participatory Surveillance in the Intelligent Building, *Design Issues*, **27**(3), 35–46.

Alexander, C.: 1964, *Notes on the synthesis of form*, Harvard University, Cambridge, MA.

Brennan, A., Alhadidi, S. and Kimm, G.: 2012, "Quokkalab". Available from: <http://www.quokkalab.com> (accessed 20 October 2012).

Calabrese, F., Colonna, M., Lovisolo, P., Parata, D. and Ratti, C.: 2011, Real-Time Urban Monitoring Using Cell Phones: A Case Study in Rome, *IEEE Transactions on Intelligent Transportation Systems*, **12**(1), 141–151.

Hall, E. T.: 1966, *The hidden dimension*, Doubleday, Garden City, NY.

Heinich, N. and Eidner, F.: 2009, *Sensing space: Technologien für Architekturen der Zukunft*, Jovis, Berlin.

Karasulu, B. and Korukoglu, S.: 2011, A software for performance evaluation and comparison of people detection and tracking methods in video processing, *Multimedia Tools and Applications*, **55**(3), 677–723.

Payne, A. and Johnson, J.: 2012, "Firefly". Available from: <http://www.fireflyexperiments.com> (accessed 20 October 2012).

Pearson, M.: 2011, *Generative art: a practical guide using processing*, Manning, Greenwich, UK.
Reas, C. and Fry, B.: 2007, *Processing: a programming handbook for visual designers and artists*, MIT, Cambridge, MA.
Reynolds, C. W.: 1999, Steering Behaviors For Autonomous Characters, *Proceedings of the Game Developers Conference 1999*, Miller Freeman Game Group, San Francisco, CA, 763–782.
Schon, D. A. and Wiggins, G.: 1992, Kinds of seeing and their function in designing, *Design Studies*, **13**(2), 135–156.
Shelton, B., Karakiewicz, J. and Kvan, T.: 2011, *The making of Hong Kong: from vertical to volumetric*, Routledge, New York.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 355–364. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

SIPHONOPHORE

A physical computing simulation of colonial intelligence organisms

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Abstract. This paper sets out to document the procedural design and implementation of "Siphonophore"; a multisensory digital ecology, mimicking colonial-ordered behaviour systems. The exploration of the notion of "self" in a complex system of highly integrated individuals with reference to the emergence of behaviours from the human-machine-context interaction, is engaged by this open system's hierarchical articulation of electronics, Arduino boards, sensors and programming routines. User interaction and recorded statistics from the system's core algorithm are assessed, in relation to the capacity of this prototype to provide an alternative methodology of describing collective intelligence, while presenting a non-standard perspective of body-space interaction and design as entertaining art. The overall impact is discussed in relation to the examined observations, towards a potential advancement to a system of superior contextual understanding.

Keywords. Colonial intelligence; multisensory installation; physical computing; spatial sensing; human-machine interaction.

1. Introduction

Great part of the interdisciplinary characteristics existing in contemporary architectural research has emerged due to the integration of embedded computation into design. Simulations, as a research resource have radically increased in quantity, as well as in the plurality of the concepts explored. Biomimetic- based simulations can operate as design initiatives, but also as analytical tools, such as in the case of agent based simulations, where the ecosystem of agents, integrated and mimicked, may vary from human populations, to flock of birds, swarms or even ant colonies. The main interest however lies, specifically in the simulations of ecologies with self-organizing characteristics, a great fraction of which is conducted in digital environments, populated by agent-members in a binary form, while contextual

parameters are programmed manually, or via an automatic recreation, such as 3D scanning.

Physical computing is progressing into becoming the medium of programming behaviours into physical objects. Therefore, the transfer of knowledge from physical systems or individual organisms into the artificial designed ecosystems is assessed by a more consistent to nature methodology, which takes into account the object's physical properties. Open-source platforms, such as the Arduino, have established a straightforwardly accessible connection between the designer and the world of electronics. Fox and Kemp (2009) argue that, designers are diverging from the figural humanoid robots to transformable systems made up of a number of smaller bots, while implementing self-assembly and multi-responsive routines into them. These new systems are accessible for architects to reconfigure them to open systems studying or inventing space.

"Siphonophore" utilizes physical computing via a biomimetic approach, towards the development of an interactive self-organizing artificial system with an inherent capacity to engage human interaction (Figure 1).

In this respect, this paper sets out to document and evaluate the design process and implementation of a multisensory digital ecology in the form of an interactive installation, mimicking colonial-ordered behaviours. "Siphonophore" is a floating system drawing inspiration, both in formal and functional terms, from the homonymous aquatic colonial organism; specifically from the Portuguese Man o' War (Iosilevskii and Weihs, 2008). It is assembled by untethered transparent helium balloon-like entities that can exist independently or connected to each

Figure 1. Siphonophore floating in an interior space.

other, forming open clusters of collective behaviours from a series of autonomous modular "organisms" that are operating together, within a hierarchy of symbiosis.

User interaction as recorded observations of a communicative experience and the retrieved statistics, such as the quantity of interactions and the detection of physical-human boundaries, are assessed in relation to the capacity of this prototype to provide an alternative methodology of describing colonial ecologies. Thus, to signify a non-standard perspective of body-space interaction and design as entertaining art, with the potential of introducing a new virtually physical, interactive spatial biotope.

2. Background

2.1. PHYSICAL COMPUTING SIMULATIONS AS RESEARCH

While focusing on a relatively new field of research, there are preceding investigations that can relate to "Siphonophore". A more elaborate comparison with previous work is out of the scope of this paper; however the following examples were crucial in assessing the accomplishment an alternative perspective to physical computing simulations.

The "Flockwall" installation, which is directly related in terms of inspiration and objectives with the presented system, is a physical simulation paradigm of collective behaviour, where an artificial flock of birds-bots is interacting with the visitors, sensing their presence in a predefined configuration outputting different light patterns as reactions to the users (Fox, 2009). "Siphonophore" differs greatly from that approach on the aspect of mobility. The modules in this case are free to "decide" their own route, thus the opposition of live design to static systems is imminent.

Two additional projects have also provided inspiration and practical knowledge. Those formal and technical systems are opposed to the dynamic emergent situations of the examined ecology and the intention of the designers to create not only a straightforwardly reacting system, but a complexity of interactions. The first one is ALAVs: Autonomous Light Air Vessels which consists of a networked objects population that communicates the concept of connectivity among people and the environment (Berk, 2007). In addition, in Festo's "AirPenguin", a group of three autonomously flying, "penguins" hovers freely through a predefined air space that is monitored by ultrasounds. The penguins are at liberty to move within this space and explore it (Festo, 2009), with the absence however of direct human interaction.

2.2. THE COLONIAL INTELLIGENCE PARADIGM

Siphonophore is a colonial (Mackie, 1986) aquatic invertebrate comprised of a number of highly specialized individual organisms-zooids that are very similar to

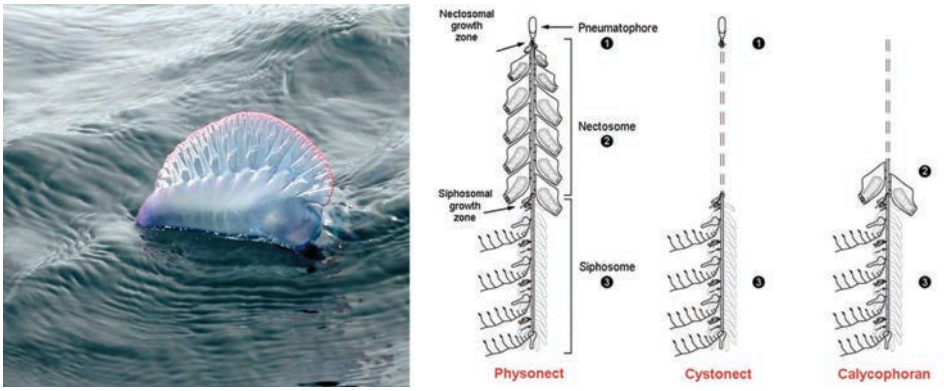

Figure 2. Physalia Physalis and its colonial structure (Image by Keith Hiscock).

organisms that exist independently in the ocean, but regarding this case are physiologically integrated and specialized in one function which makes them dependable from the other zooids as part of the colony. As Casey Dunn (2009) indicates "Being a Siphonophore is as if you were to bud thousands of conjoined twins throughout your life, some with only legs to move everybody, others with only mouths to ingest food, others with enlarged hearts to circulate the shared blood, and others fully dedicated to the sexual production of new offspring colonies."

A specific type of the 175 known species of Siphonophores is chosen, both for its morphological attributes, but also for the hierarchical structuring of its functions. This genus is the Portuguese Man o' War or Physalia Physalis (Figure 2).

3. Siphonophore: A Digital Ecology

3.1. COLONIAL INTELLIGENCE ELEMENTS

The system operates as a tree at the root of which lies the main "brain" of the colony. The rest of the members operate on equal terms, following their inherent "intuition" sensing spatial qualities, reporting back to the "brain", which coordinates their decisions. All the members can exist independently within the environment, in opposition to their symbiotic character.

The "scout" members of the colony are balloon-like structures, possessing a certain amount of intelligence; flying around feeling people's presence, while reacting to boundaries and physical obstacles. The locomotion of the entity is achieved by two embedded motors, while sensing is addressed through capacitance sensors and the "feelers". When stimulated by any kind of incentive, they modify their behaviour, by changing their direction and by altering the blinking patterns of the integrated on the

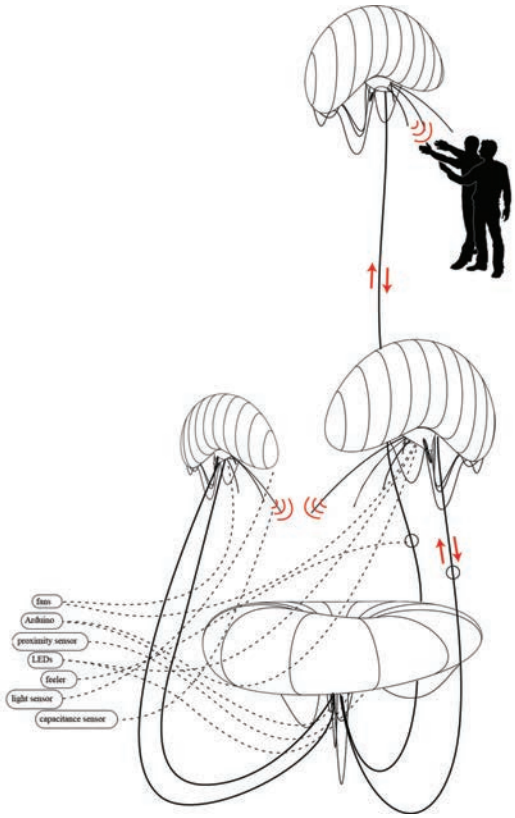

Figure 3. Graphic representation of the Siphonophore colony displaying the individual entities.

structure, LED lights. The "scouts" communicate with the "brain" transferring light signals in a vice versa mode. The "brain" can also move in a vertical mode by switching the spinning direction of his central fan, while calculating its distance from the ground by a proximity sensor, and at the same time outputting values of flotation while co-defining along with the LEDs outputs, its behavioural patterns. In the final installation, two "scout" entities were connected with the main "brain" (Figure 3).

3.2. DESIGN THROUGH MAKING

The flotation attribute has sculpted most of the ecology's geometrical and morphological properties. Each entity had the capacity of bearing the load of an Arduino board, fans, motors and circuits, but also as a result of each member's independency, a personal power source had to be embedded onto its structure. The

entities could also suffer a process similar to physical death, when the power run out or if destroyed during the implementation. This notion engages the actual delicate nature of Physalia Physalis, combined with the necessity for transparency and reflectivity. Something that made extremely complex to address a material system, which is lightweight and at the same time capable of withstanding the load of the system's robotics without tearing.

Instead of being a top-down design process, "Siphonophore" is portrayed by the authors as a "design through making" procedure. The final result was the outcome of multiple testing in morphological configurations, overall sizes, materials, types of electronics and hardware, with a total of over forty developed prototypes.

3.3. PHYSICAL COMPUTING MODULES

Programming the behaviour and kinetic attributes, engaged coding in the Java based environment of the Arduino platform. The code is moderately simple as the analogue inputs, such as light sensing, capacitance and proximity are flowing in constant loop from digital commands back to analogue outputs of blinking patterns. Whereas, while coding for performance, the Processing language was utilized to manage and organize the great amount of simultaneous signals into a digital list that would be accessible by the algorithm of the decision making "brain" of the colony. Processing was also employed to code the data collection algorithm, which would map, the position of the colony entities at regular time intervals, enumerate the interactions, as well as the duration this interaction was in effect.

The hardware elements of "Siphonophore" can be comprised to the following. Two 9V motors with fans that placed in each entity, with the exception of the "brain" where only one motor is used. Lightweight cables within each member to utilize light and capacitance sensors, LEDs and the "feelers"; long metallic medium stiffness cables that bend while hitting a boundary, sending analogue signals on the input pins, altering the direction of the "scout" (Figure 4). The "brain" is also connected to a computer, through a USB port in order to record the data from the algorithm.

3.4. ASSEMBLY

Thin transparent polyester film which partially reflects the light signals produced by the LEDs was used in the final assembly. Those films were cut and heat glued together through ironing. In addition, the electronics bearing frames are created by stiff 1.5 mm frosted polymer plastic, capable of bending. The toroid morphology of the "brain" intends to differentiate it from the rest of the entities (Figure 5).

The necessity of cavity development for the robotic elements embodiment into the structure has lead to an organic configuration for the scouts. The arc shaped

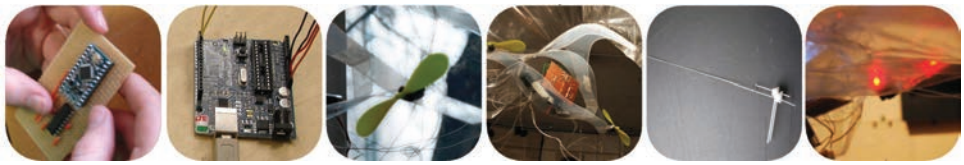

Figure 4. Overview of the hardware physical computing elements of "Siphonophore".

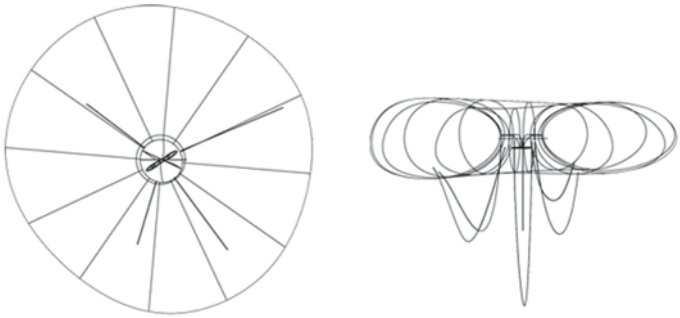

Figure 5. Plan and rear view of the "brain" entity.

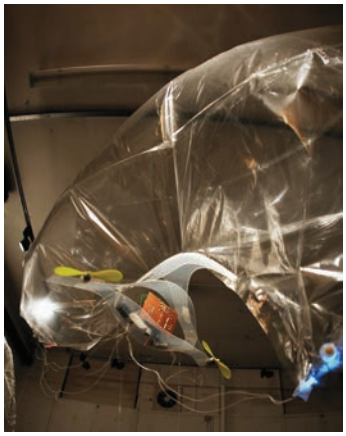

Figure 6. The "scout" entity.

polymer component (Figure 6) fits into the lower part of the balloon, while the fans are placed in a symmetrical manner to its two edges, attaining maximum freedom in rotational movements. A valve is also attached to each one of the modules in order to extend the entity into a re-usable helium assembly.

3.5. PROGRAMMING BEHAVIOUR

Mimicking colonial intelligence via a materialized approach is not meant to reduce interaction into the contextual framework but advance it to the human-machine interface. To this respect, the interaction focuses on an anthropocentric – user friendly approach, and can be summarized into a form of linked behaviours. The context and the human user stimulate the inputs of the system, while the ecology processes the data and outputs certain behavioural patterns (Figure 7).

The “brain” adopts certain moods by the processing of the data coming from its relevant position to the ground and the light signals from the “scouts”, returning at the same time light signals to the “scouts” affecting their trajectories.

“Siphonophore” implements a reactive character which is somehow ambiguous compared to the original organism. The collective output of the system appears as aggregated emergence between individual actions rather than being influenced by particular cases of interaction, deduced to its complex symbiotic nature. The recorded data of both human and environmental interaction act as a form of digital psychogeography, a mind-map for the colony’s journey.

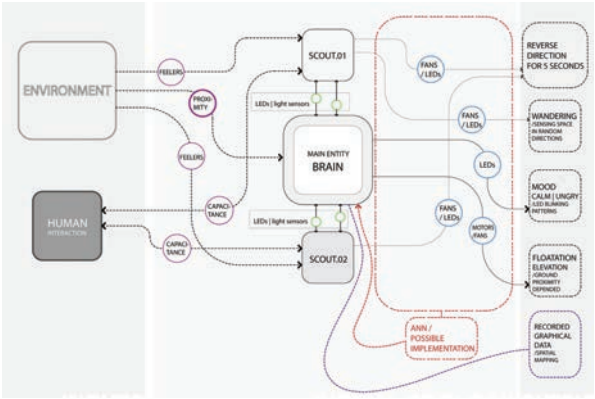

Figure 7. Behavioural diagram of the digital ecology.

3.6. DATA AND OBSERVATIONS

Recorded observations from the installation can be either still images or videos illustrating in a more coherent understanding of “Siphonophore’s” behaviour. Interaction and the user’s reactions, blinking patterns and routes (Figure 8), become more apparent through the analysis of the recorded data, leading to repeating and emerging patterns.

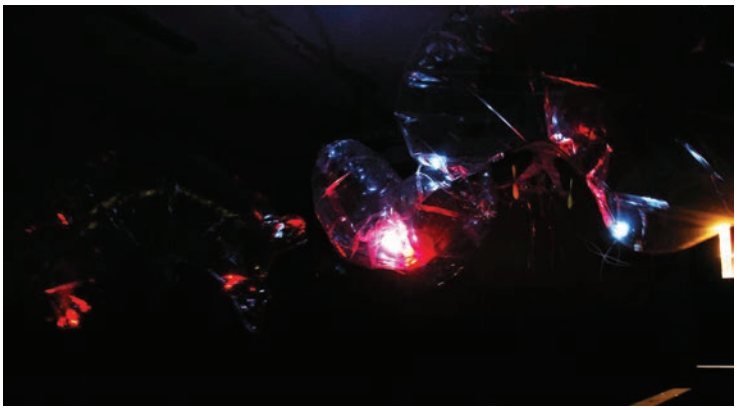

Figure 8. Blinking Patterns of the "Siphonophore".

Figure 9. Scout's routes – the size of the circles is equivalent to the duration of interaction.

The algorithm of the integrated recording routine, tracks the position of every member of the colony at regular time intervals into a local metric reference system, assisted by a ceiling to floor facing recording camera. By this method, the routes of the "Siphonophore" elements can be exported in a text document, along with the number of interactions, both human and spatial, collisions, as well as the duration of each interaction. Data can then be interpreted into graphical representations, illustrating the complex performance-based mapping of the existing space (Figure 9).

4. Conclusions

In "Siphonophore" the integration of physical characteristics into the illustration of the built-human context, has presented a solidified eco-system of "affordances" and interactions; while the aggregated emergence of collective actions rather than certain stimuli-based reactions, is reinforcing the notion of symbiosis diverging from any preceding approaches existing in the field. As Michael Weinstock (2010) argues "organisms and the ecological systems within which they exist have evolved from the interactions of elements that combine into a variety of 'assemblies'. Some

'assemblies' survive and go on to become integrated into more complex 'wholes' that evolve through natural selection." In the case of "Siphonophore" this evolution is replicated within the relationship of space and social activity. However any references to actual architecture are limited, as this system can be primarily interpreted as an ephemeral installation.

The hypothesis of a physically digital mimesis can be expanded to notions like spatial mapping, exceeding the designer's initial expectations. Possible implementations in an unambiguous architectural research context would be motivating and valuable in terms of spatial sensing due to the system's proved capability to map through its own perspective of programmed behaviours. That leads not only to a passive random mapping but in a dynamically defined one, affecting the mapped, as its playful character attracts human interaction and curiosity. In future development, "Siphonophore's" capacity can be upgraded through the implementation of a learning process algorithm. The use of an Artificial Neural Network will organize the emerging behaviours of the system and coordinate its performance. Knowledge is gathered through previous encounters of the systems entities with spatial boundaries, allowing memory based association of activity, providing a unique emergent behaviour in the form of an alternative optimization methodology for the particular system.

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References

Dunn, C. W.: 2009, Siphonophores, *Current Biology*, **19**(6), R234.

Fox, M.: 2009, Flockwall: A Full-Scale Spatial Environment with Discrete Collaborative Modules, *ACADIA 09: reForm( ) – Building a Better Tomorrow*, Chicago, 90–97.

Fox, M. and Kemp, M.: 2009, *Interactive Architecture*, Princeton Architectural, New York.

Iosilevskii G. and Weihs, D.: 2008, Hydrodynamics of sailing of the Portuguese man-of-war Physalia physalis, *Journal of the Royal Society – Interface*, 613–626.

Mackie, G. O.: 1986, From Aggregates to Integrates: Physiological Aspects of Modularity in Colonial Animals. *Philos. Trans. R. Soc. B Biol. Sci.*, **313**, 175–196.

Weinstock, M.: 2010, *The Architecture of Emergence: The Evolution of Form in Nature and Civilisation*, John Wiley, London.

Berk, J.: 2007, "ALAVs: Autonomous Light Air Vessels". Available from: <http://www.alavs.com/> (accessed 29 March 2012).

Festo: 2009, "AirPenguin". Available from: <http://www.festo.com/cms/en-us_us/10296.htm> (accessed 29 March 29 2012).

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ASSIMILATING INTERACTIVE TECHNOLOGY INTO ARCHITECTURAL DESIGN

A quest for developing an 'architectural drawing' for urban interaction design as a communication platform through combining physical sensing devices with simulation software

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Abstract. The research presented in this paper investigates the need for an equivalent of architectural drawings for urban interaction design in an architectural scale in order to communicate interaction design intentions to design participants and clients through using state of the art computer, gaming and sensor technologies. The paper discusses two projects (a) Blur Building, as a large scale interaction design project executed through an experienced team and (b) presents as student design project coordinated by the researchers as a reference project. Both projects in this paper are discussed and evaluated from an Urban Interaction Design point of view. This paper emphasizes the significance for establishing 'drawing' equivalents for urban interaction design, discussing representation of ideas in architectural design; followed by outlining existing methods of interactive design representation, such as storyboards to then introduce current advancements in gaming environments. The following paper introduces a framework for future research projects that will design, deploy and evaluate of prototypes as a communication platform combining physical sensing devices in combination with gaming engines to enable a digital / physical hybrid. This would allow designers and clients to test, evaluate and improve urban interactions in a design phase prior to completing the project.

Keywords. Spatial design; human-computing interfacing; interactive architecture; smart environments; sensor technology.

1. Introduction

The aim of this paper is to outline a possible transition of how urban interaction design is communicated to design collaborators and clients in order to (a) develop

and communicate ideas with one platform; (b) assure an easier understanding of the design for non-educated clients; (c) test and simulate the design prior to installation and (d) evaluate and visualize real-time changes to the design.

Urban interaction design is an area of research and development that focuses on creating autonomous reactions for users within a space. These reactions can be a visual or physical change in the environment to express information or aid in creating an improved space (Buxton, 2007).

Fabrication of interactive environments pose issues with trying to acknowledge how users will react, experimentation on a micro level to observe user and component can be beneficial, however on a macro scale when a user is immersed in an autonomous environment can change how the user will understand and interact with the space. Two methods of design representation, Storyboarding and 3D gaming environments will be evaluated.

The aspects foreshadowed in the introduction above lead to the following observations that are further outlined when setting the scene by analysing two projects: Blur Building by Diller Scofidio + Renfro and a student project called "Hypersurface Architecture [Redux]" coordinated by M. Hank Haeusler, Sally Hsu and Danny D. Nguyen, outlining observations made by analysing the two projects that then lead to the core research question. Subsequently the paper will then present first research findings that work towards answer the question.

2. Research Background

The motivation for choosing the two above-mentioned projects is based on the extensive documentation that has been recorded. Each project gives insight to the processes and challenges undertaken by The Blur Building's experienced team on a large-scale project and the student design team on a smaller-scale project.

The Blur Building highlights in particular the communication undertaken by the design team and sponsors that lead to changes in the design due to confusion of design direction.

The student project enabled the coordinators to take the role as a "client" to observe processes from a research perspective of design decisions made by the students and how interactive design was created, tested and experimented within the time frame of the project.

Both observations and analysis of the projects were based purely on the aspect of designing an interactive spatial environment in order to argue for the significance of establishing an 'architectural drawing' equivalent for interactive spatial environment.

2.1. THE BLUR BUILDING

The Blur building by architects Elizabeth Diller and Ricardo Scofidio was the centrepiece pavilion of the sixth Swiss national exhibition 2002. The design was to incorporate approximately 31,400 nozzles that sprayed mist into the air, which allowed the exterior of the structure to be shrouded and look similar to a cloud (Diller and Scofido, 2002). Prior to entering the cloud, each visitor responds to a questionnaire/character profile and receives a "braincoat" (smart raincoat). The coat is used as protection from the wet environment and storage of the personality data for communication with the cloud's computer network. Using tracking and location technologies, each visitor's position can be identified and their character profiles compared to any other visitor. As visitors pass one another, their coats will compare profiles and change colour indicating the degree of attraction or repulsion, much like an involuntary blush – red for affinity, green for antipathy. The system allows interaction among 400 visitors at any time.

2.1.1. Explaining design process for interaction

During the initial phases of designing the Blur Building, many different ideas were conveyed in regards to how users interact with and within the Blur Building. For example, Ben Rubin a contributor to the Blur project introduced an idea to use "smart raincoats or braincoats" that will allow users to autonomously connect to one another like online dating (Wolfe, 2006). The matchmaking was based from questions that were asked by an automated voice prompter embedded in the coat itself, depending on the answer, it will begin to guide the wearer to users with similar responses. However, influence from their major sponsor saw that ideas were lost because a lack of understanding from the Sponsor's executive board members, "Some of the executive members were lost and had no sense of the project direction anymore" (Diller and Scofidio, 2002). This onslaught of confusion between designer and audience resulted in the Blur Building to negate any interactive elements and to only show the building.

The Students have used state-of-the-art computational architectural methods to design physical pixel building components that when assembled form the media walls. Each media wall comprises 300+ Pixels as 'digital bricks'. Each 'Digital Brick' has been generated following the same design logic with a scripted variation in order to achieve a gradient from small to large size and to enable them to be assembled as a complex curved non-Euclidian surface. Each 'Digital Brick' contains an AHL S18 LED to transform an otherwise static wall into a dynamic media wall that is able to showcase interactive media content transforming the installation into a vibrant light sculpture.

Figure 1. Picture of two installations (left to right: detail view, situated on site, detail view).

2.1.2. Explaining design process for Interaction

The student project required the use of an interactive element that will be displayed on the Wall Installation. Parameters of the interaction were based on available devices, budget and spatial environment of the Customs House in Sydney. Due to the parameters, tests were completed to make aware of the types of devices that allowed information to be captured in an environment and streamed to a computer. The devices that were selected for the interactive element of the project were a wireless webcam and microphone. Both of these devices allowed data to be streamed into a simulation program that re-contextualizes the streamed data to produce images that would be displayed via the LED system. The interaction that was chosen for the each wall based on the device was:

- **Webcam Wall:** A digital ball floated in random directions on the wall, and as users were detected by the webcam, the ball would follow the user and begin to change colours randomly.
- **Microphone Wall:** An animation of several lines moved across the wall surface, and as users created sound, more lines would appear.

The studio was successful in being able to produce 2 interactive walls that were displayed in a public domain. Both walls functioned as specified by the design brief, however noticeable flaws in the post fabrication phase highlighted areas in the interaction that were overlooked due to the complexity of designing for public users. The surrounding environment of the exhibited walls inhibited the users to become immersed into the interaction and understand completely the ideas the students were trying to convey through interaction.

3. Research Question

What observations did the researchers make by (1) investigating a large scale interaction design project executed through an experienced team of various reknown designers that have to communicate their interaction design idea to either themselves or to their clients; and (2) executing a studio on their own in which we were able to place ourselves, as tutors, into the role of the clients of a project where students need to communicate their interaction design ideas?

Both investigations outlined following observations:

- **Blur Building:** design interaction was conveyed to sponsors via visual imagery; however it still created confusion, as the blur structure created an environment that would have further expanded the experience of the interaction. Without proper understanding of the environment, there is a key element that is missing from the overall 'package' of the interaction proposal to client.
- **Student project wall:** Though simulation programs were used to evaluate the interaction and design of the wall, the spatial environment was not considered thoroughly for the end public user, as they are being immersed into this interactive element, the surrounding environment hinder their experience.
- The ability to test and understand how users would interact with the wall was not made apparent in both case studies.

Based on the above listed observation and the aim of the paper is to demonstrate the significance and vision of research in terms of a central question to the research:

> *What would be the equivalent of architectural drawings (plan, section, elevations) for interaction design in a public urban domain, on an architectural scale, in order to communicate interaction design intentions to design participants and clients through using state of the art computer, gaming and sensor technologies?*

In answering the research question, the objectives for the research in general are: to investigate related research and projects in the area; to research designer and client requirements in regards to communicating and understanding interaction designs; to design, deploy and evaluate prototypes as a communication platform using state of the art computer, gaming and sensor technologies. More specifically this paper will, due to its limitation in size, outline the significance of such undertaking by discussing representation of ideas in architectural design; followed by outlining existing methods of interactive design representation, such as storyboards to then introduce current advancements in gaming environments. Thus the presented paper introduces a framework for a research project that will work towards designs, deployments and evaluations of prototypes as a communication platform

using state of the art computer, gaming and sensor technologies. The paper wants to conclude with a vision for the research and the research projects to come by introducing the next steps of the project.

4. Forms of Representation of Design

This section introduces current forms of design representation of how designers communicate their concept to clients that do not have the same understanding as the designer. The method used to communicate knowledge is to help gain "attention, inspire recipients, to anchor a message through addressing emotions, to improve recall or to provoke discussions" (Burkhard, 2004). Current forms of design representation will be addressed, and how such methods are being applied to interactive design, through methods of storyboarding and Gaming Environments.

4.1. METHODS OF DESIGN REPRESENTATION

Burkhard (2004) describes Architects as being experts of design representation, as they are at the centre of such projects where a cluster of engineers, designers, and contractors all must have a similar understanding of the project. Sketches, drawings and 3D renderings are a similar form of visually communicating information and have been successfully used to transfer knowledge. Brody (1982) suggests pictures can "excite the learner, explain difficult concepts and expand the written narrative". However, communication of ideas can be hindered when the concept itself, requires the use of individuals to partake in its design to allow an immersive environment to be created through physical human behaviour to further expand the potential of the design. Therefore, interactive design with the purpose of human interaction can be a difficult outcome to achieve, because though such methods as storyboarding and imagery exists, there is a lack of "emotive behaviour" that is found with human interaction, as such design representation can only interpret a probability of events (Wiethoff and Gehring, 2012).

4.1.1. Storyboarding

A storyboard is comprised of several images that are used to communicate designs to clients through depicting imagery of design, functionality and interaction within context. Within the area of designing interaction, storyboarding has allowed designers to methodically explain during prefabrication phase, how their design functions, and the triggers of interaction within the design. The use of storyboards forces the designer to evaluate the implications of designs that could be adherent

to abstract concepts (Van der Lelie, 2006). However, as such, a designer can only simulate the possibility of how a person will react with the design in their storyboard. This could result in designs not functioning as intended, because there was a lack in understanding emotive behaviour from humans that do not share similar thoughts or interaction processes as depicted in the scenarios created in the storyboard.

4.1.2. Gaming Environments

A gaming environment is an immersive world a person can access through controlling an avatar, which is an object that is able to interact in the gaming environment. Dependent on the game itself, the avatar is able to interact with objects, other people and be a part of changes that occur within the game. Each avatar is controlled by a real person, subsequently means that the avatar's behaviour in game reflects the player's own emotive state (Warburton, 2009). This idea has been used to create environments that can simulate situations that would be either impossible or difficult to create in real life. For example, Drettakis et al. (2007) discuss how gaming environments can be used to simulate Architectural design of interior and exterior space and shell of a building to involved users/clients. Therefore gaming has evolved to being a capable tool in design simulation.

This form of design representation can be extended to allow simulation of interactive designs to be tested by users in a virtual gaming environment. Though this form of representation is advancement to the aforementioned method of storyboarding, there lacks a quality of immersive environments that is attached to designs that create or develop in spaces that is occupied by users or current objects that can influence actions of the user. The main interest is not in designing interactions for existing spaces or for existing gadgets but for using interactivity as a design parameter to define space.

5. Research Project – Physical and Digital Parallels

The paper has investigated how design representation to clients and collaborators without prior specialist knowledge can cause confusion and also bypass untested elements of the design. Though there are techniques such as storyboarding, and 3D gaming environments, it still lacks the interactive element that is achieved through human emotive behaviour of a user that is immersed in the interactive environment. With the research question established, development of an alternative method of design representation through bridging physical prototyping and computer simulation technology can be used. The purpose of the connection is to

allow users to be immersed in an environment that has been created by simulation software and also interact with physical components, this interaction gives users the ability to test interactivity and also see a result through the computer simulated model. The combined method of computer simulation and physical prototyping can create an improved understanding of how the user will behave in an interactive and immersive environment.

During the next stage of this research, a review of current devices and techniques will be observed to determine how current forms of Urban Interaction Design are being implemented. This will give precedence to experiment with alternative means of communicating Urban Interaction Design to users and also make available visual representation techniques that adhere to the unique properties of interaction design. The experiment will look into devices that give users the ability to interact with digital objects in a physical space, such as the Kinect system which has been gradually increasing as a powerful tool in Human-Computing Interfacing field (Giles, 2010).

To examine the interaction quality of these devices with digital simulations, a goal of the experiment will be to create a rectangular border comprised of equal cubes. However, only 2 cubes will be physical components, whilst the rest will be made up from a digital simulation that is being projected on the surface. The connection that is to be achieved will have the physical cubes interact with the digital system, as such if the physical cubes are moved inwards or outwards, then the digital simulation will adjust accordingly to the physical components, giving the impression that the 2 systems are working in unison. This combination of physical and digital technology gives users access to understanding through visual aids and physical touch. The success of the experiment will allow further testing for larger-scale projects and the examination of creating immersive environments developed from digital projections and physical components that both aid in representing the proposed interactive design to the end user.

6. Conclusion

Modern forms of representation in Architectural design, such as static imagery, video and 3D gaming environments are a common practice to visualize and communicate design information. However, as such these forms of design representation can also lack a level of detail when physical or mental interaction is required by the user. Current forms of representation can only give users a minimal level of interaction understanding, however lacks the important level of human emotive behaviour when they are not only inter- acting with the design, but also immersed in the spatial environment.

The case studies chosen for this research paper, demonstrated how difficult design interaction can be visualized by users without specialist knowledge. The Blur Building case study focused on the design representation stage where the sponsors disregarded many different interaction designs due to their lack of knowledge in understanding the intentions of the designers in the storyboards and did not visualize the interaction on a holistic view when coupled together with the immersive fog structure. The Architectural Computing Studio demonstrated how concept design from sketches and computer simulations still did not foresee the issues that pertained to how the Interactive Walls were placed within the spatial environment and the affected visual interaction design. Thus the aforementioned case studies give precedence to determine an area of research that can introduce an alternative form of communicating Urban Interaction design to collaborators and clients that lack specialist knowledge and improve interaction design awareness.

References

Brody, P. J.: 1982, Affecting instructional textbooks through pictures, *The technology of text*, **1**, 301–316.

Burkhard, R. A.: 2004, Learning from architects: the difference between knowledge visuali-zation and information visualization, *Information Visualisation, 2004. IV 2004. Proceedings. Eighth International Conference on*, IEEE, 519–524.

Buxton, W.: 2007, *Sketching user experiences: getting the design right and the right design*, Morgan Kaufmann.

Diller, E. and Scofidio, R.: 2002, *Blur: The making of nothing*, Harry N. Abrams.

Drettakis, G., Roussou, M., Reche, A. and Tsingos, N.: 2007, Design and evaluation of a real-world virtual environment for architecture and urban planning, *Presence: Teleoperators and Virtual Environments*, **16**(3), 318–332.

Giles, J.: 2010, Inside the race to hack the Kinect, *The New Scientist*, **208**(2789), 2223.

Van der Lelie, C.: 2006, The value of storyboards in the product design process, *Personal and Ubiquitous Computing*, **10**(2), 159–162.

Warburton, S.: 2009, Second Life in higher education: Assessing the potential for and the barriers to deploying virtual worlds in learning and teaching, *British Journal of Educa- tional Technology*, **40**(3), 414–426.

Wiethoff, A. and Gehring S.: 2012, Designing Interaction with Media Facades: A Case Study, *DIS '12 Proceedings of the Designing Interactive Systems Conference*, ACM, New York, 308–317.

Wolfe, C.: 2006, Lose the Building: Systems Theory, Architecture, and Diller + Scofidio's Blur, *Postmodern Culture*, **16**(3).

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 375–384. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

COLLECTIVE INTELLIGENCE: AN ANALYTICAL SIMULATION OF SOCIAL INTERACTION WITH ARCHITECTURAL SYSTEM

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Abstract. This paper proposes an architectural system interactive to both users and the environmental condition in real-time. While nature acts as a global control for the system, the user can alter it locally. Due to the increasing digitization of our contemporary culture, there is an unprecedented capacity for information to flow in our physical and socially net-worked world that can be used to inform design problems and processes. Live and real-time information sources, like Twitter, could be virtually scanned for specific data input associated to a particular geometrical manipulation. This process enables a collective group of users to inform the system. As the number of users increases there is collaboration for defining the form which is different from single user interaction. Since the model is associated with a specific definition of generative behaviours as described by the words, these definitions could be used as the keywords to manipulate its form. In this research these keywords act as data input from Twitter account and the model reacts in real-time and its form changes according to that specific keyword. An analytical simulation runs over the digital model which has been conceived by users to show how it is performing according to environmental conditions.

Keywords. Real-time data streaming; crowd-sourcing; interactive architectural system.

1. Introduction

With continual shifting of the technology implementations into architecture, an understanding that building by nature is dynamic in character and is therefore necessary to develop more sustainable and environmentally oriented architecture. In this line of research, there is a growing interest to construct physical systems which have the ability to actively respond to local climatic conditions and social settings, allowing inhabitants to continuously inform and adjust local climates and

their enclosures from both phenomenological and functional perspectives calls for new design approaches that place spatial performance and perceptual issues at the core of design methods and models. In order to make architecture more efficiently responsive to both users and natural environment, architecture should be understood as an ecology, involving dynamic and varied relations and mutual modulation between material systems, macro- and micro-environmental conditions, and individual and collective inhabitation (Hensel and Menges, 2006).

Many visionary architects have urged for a radically new way of approaching architecture that would allow it to embrace the new opportunities of our time:

> "Until now architecture was a discipline of intractability. Buildings were always meant to be as steady as a rock and give shape to the flow (of people, energy and matter) and, more importantly resist that flow. Let's imagine that buildings and built environments are becoming programmable. Form and substance can both be driven. An interactive relationship will effortlessly grow between the users and smart appliances are beginning to communicate now. Buildings will develop into a smart swarm of building parts in contact with each other and with their users" (Oosterhuis, 2001; Jaskiewicz, 2010).

Some of the more recent efforts link such approaches to the idea of architectural systems being an integral part of their surrounding environment with the proclaimed need of upholding a constant exchange with the same. The Blur Pavilion by Diller + Scofidio is an example of this approach, rather than being a closed system trying to separate itself from it. However, most of these researches consider architecture as a responsive system either to its users or nature. While the former gives control to the user to adapt the system, it fails to be compatible with environmental factor. Therefore, the system does not benefit from natural element such as day-lighting and natural ventilation among others; by the same token, the latter is not a fully efficient system be-cause it does not take into account the needs/intentions of the users. In this system users' variable does not affect the process of form finding. So the result form, although compatible with environmental factors, may not be desirable for the users because there are many unpredictable user-related variables which may influence the efficiency of the system.

This paper outlines new experiments, in which physical prototype models are driven by live input from local weather data and online social networks. This design framework integrates user intentions, computational techniques and environmental conditions leading to a performative prototype which aims at providing optimization and compatibility. The outcomes of the research show promise of structural integrity and responsive reaction of the prototype model to live information input by online crowdsourcing and climatic condition.

2. Interactive Architecture (IA)

Responsive architecture is any kind of architecture that has the ability to respond to users' needs (Sherbini and Krawczyk, 2004) and environmental conditions. While responsive architecture means architecture that just reacts to users' actions, interactive architecture strictly implies a reciprocal relationship between architecture and its inhabitants and an inherent learning process of both. An adobe wall, for example, responds to outdoor temperature where it keeps cold air in the house when it is hot outside. It is a material property; it is not out of an intelligent processes. However, interactivity in synchrony with its definitions (e.g., Haque, 2006; Oosterhuis et Xia, 2007), interactive architecture can be defined as architecture that exhibits autonomous behaviour, in which that behaviour evolves through inter-actions with its users and environment (Jaskiewicz, 2010).

2.1. RESEARCH APPROACH TO IA

This paper therefore illustrates a research agenda aiming at understanding the morphodynamics of architecture through both communication with the natural surrounding and interaction with users in real-time (Hensel and Menges, 2006). Therefore, it combines both functional and phenomenological aspects of interactive systems by exploring physical prototypes and pro-cessing adaptive behaviours that respond to climatic conditions as well as social parameters. In doing so, the intention is to set up a time based adaptive domain, applied through learning algorithms classified as 'intelligent' system which meets these criteria:

- Input system that receives information by means of information receiver
- Processing and information analysis
- Output system that reacts to the input in form of a response
- Time consideration that makes the response happen within the needed time
- Learning ability (Sherbini et Krawczyk, 2004)

3. Collective Interaction (Intelligence)

One of the key questions to be answered when conceptualizing interactive urban space is how information flows in to be organized? One aspect is the flow of information within the interactive system itself. The other, more significant, aspect is the flow of information between Interactive system and its users. Culturally, we are accustomed to the idea of humans controlling all artificial systems. The notion of control, however, refers to a one-directional mode of communication, which stands in opposition to the idea of interactivity that entails an inherently reciprocal relationship. Nevertheless, the following models of control in architecture are

by analogy also applicable to interactive architecture, assuming that the relationship of control can be substituted by the relationship of the mutual affect.

Two elementary models for user control of participatory of architecture (both presented at the same conference in 1971) belong to Yona Friedman, the "Participatory Architecture" (Friedman, 1972) model, and Charles Eastman, the "Adaptive-Conditional Architecture" (Eastman, 1972) model. Friedman's model puts building users in direct control of architectural adaptations, through one, centralized interface and control system, which coordinates all architectural adaptations within the given context. Conversely, Eastman's model proposes a distributed system of installations and devices that operate autonomously and are individually controlled by building users through local (negative) feedback loops. Tristan d'Estree Sterk reintroduced models of Eastman and Friedman to the contemporary discourse and proposed another model combining the two, which he calls the "hybridized model of control" (d'Estree Sterk, 2006), where both local and global (top-down and bottom-up) control is possible (enforced either by users or by "intelligent processes"). By generalizing this classification, interactive system models can be ordered along the line of their increasing distribution and flexibility and decreasing centralization (shift from global, through local, to no coordination).

Any kind of such models requires communication between at least some of its autonomous components, and thus can be treated as a multi-agent system (MAS). MAS are typically developed in software, but can also be found in robotic applications (e.g. swarm-bots (Mondada et al, 2004)) and are often associated with development of artificial intelligence (Russel et Norving, 2009) (e.g. swarm intelligence). MAS can consist of simple-reflex or learning (intelligent) agents. Many of the existing MAS models include coordination or control mechanisms operating in parallel to distributed agent processes. There are numerous established models of such 'hybridization' with varying degrees of importance of coordination or control, listing of which is beyond the scope of this paper. Generic MAS models are thus an obvious foundation for development of more specific models for interactive architecture with multiple users (Jaskiewicz, 2010).

4. Interactive Model

The experimented prototype is a canopy designed for an open public space which has been developed through a workflow with these three parts:

- Part one: provides a user interface through a web-based interface, Twitter account and Processing, which enables users to communicate with a parametric model of the canopy in grasshopper and manipulate that.

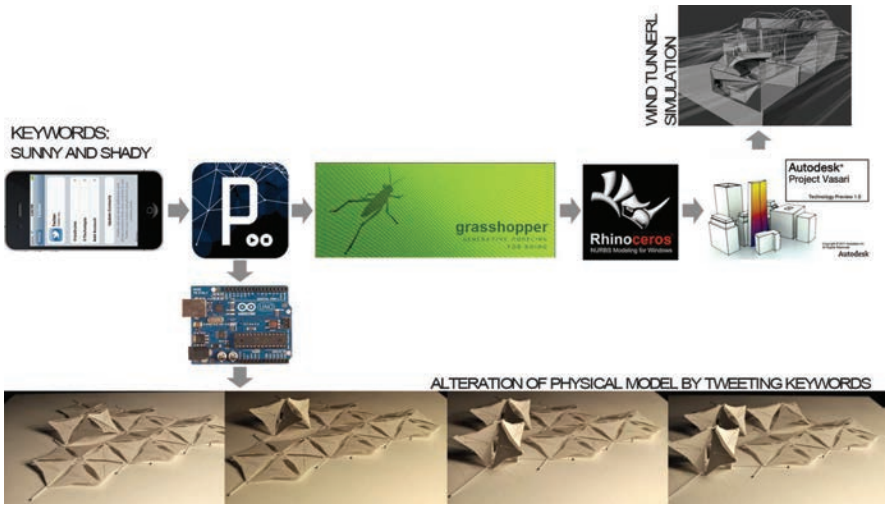

Figure 1. Flow of Data in the Interactive Model.

- Part two: Connection between a physical model, identical to the virtual model, through Arduino and Servos that alters based on changes made by users accordingly.
- Part three: links between the parametric model in grasshopper, and an analytical simulation in Vasari through Revit Python Shell to evaluate the performance of the model (Figure 1).

4.1. USER-INTERFACE

Processing is an open source which is a java-based programming language and development environment created by Casey Reas and Ben Fry from MIT, for designers who want to create images, animations, and interactions; processing initially developed to serve as a software sketchbook and to reach fundamentals of computer programming within a visual context (pro-cessing.org). In addition, it facilitates physical devices such as Wiimotes, cameras, Arduino, sensors as well as Web 2.0 data (such as from Twitter) to be connected to various parametric design software, such as Rhinoceros 3D, Grasshopper and 3ds Max, Maya and other modelling programs.

Through the Processing a script has been developed which is built on the concept of publish-subscribe software architecture. It utilizes the User Data-gram Protocol (UDP) and a central server. The server publishes information from various sources, such as sensors, the web, Arduino, or other physical interfaces. Parametric software, grasshopper, as well as Web 2.0 data can get connected through the server to obtain real-time updates. The UDP connection has been

developed through processing and grasshopper for this project can be programmed as custom features, plug-ins, or scripts of the associated software or hardware interfaces. The software architecture is extensible, flexible, and allows integration with any platform that supports UDP network protocol.

This script enables users to inform a parametric model in Rhino, grasshopper, utilizing the power of social networks. This enables crowdsourcing for collaborative form finding. Through this process, form finding and control of the system is no longer restricted to individuals and it enables a crowd of people in a public space to have control of the form of the physical realm.

The crowd needs to have an access to a Twitter account, and post keywords to a specific "hashtag" associated to a particular Twitter account. (Salim et al., 2010a) The keywords, which are associated to particular geometrical manipulation of the physical model, in this example: Shady and Sunny which are defined and simplified based on the function of the element to be user friendly.

Processing reads a Twitter stream and scans for these keywords, shady or sunny. If keywords are found, data are sent via UDP directly to Grasshopper. Since the Rhino model is associated with the Grasshopper definition of generative behaviours as described by the keywords, the model gets updated accordingly whenever a keyword received in the buffer (Salim et al., 2010a) (Figure 2 and 3). It takes five seconds for processing to filter the account and every five seconds it updates the result.

The similar process is devised for the geo-location of user. User can also tweet its location (the longitude and latitude,) this coordination is associated with an

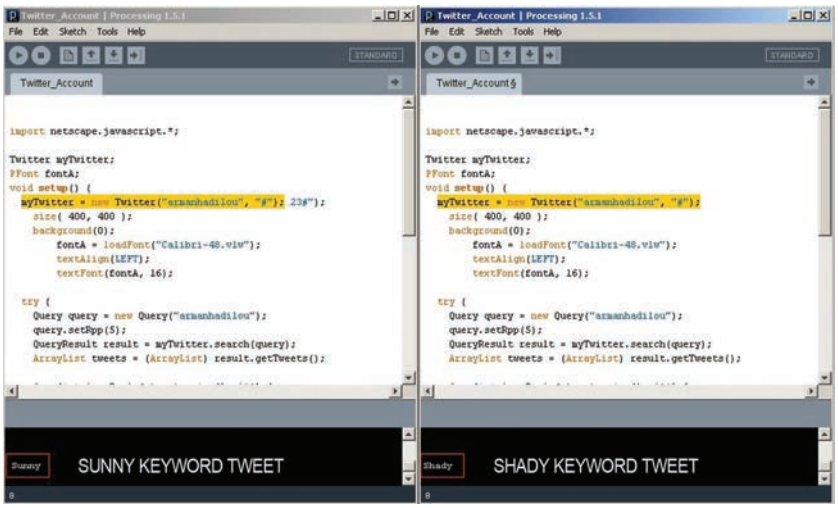

Figure 2. Processing scans the twitter for keywords (Sunny and Shady).

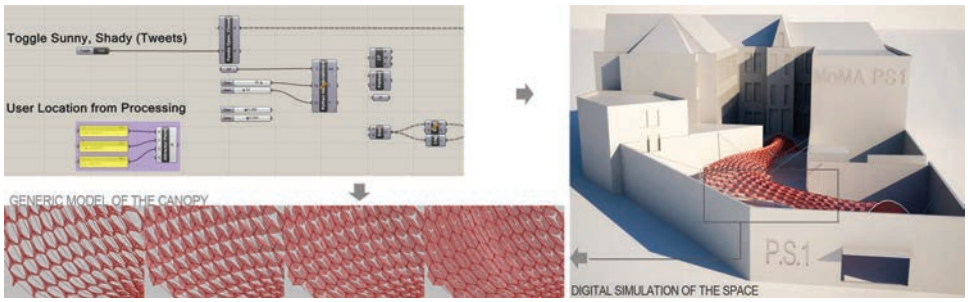

Figure 3. Updated model in grasshopper based on tweeted keywords.

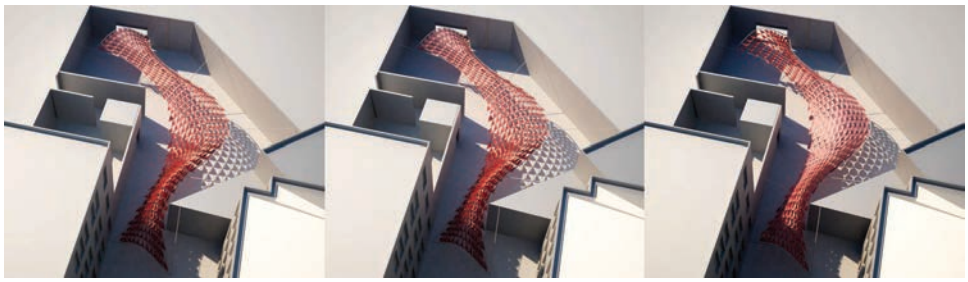

Figure 4. The enclosure of the canopy changes with the movement of users.

attractor point in grasshopper to the virtual model which affects a certain number of modules in its proximity (Figure 4). The location of the user affects a 6x6 grid of modules centred to the location of point. Using the specific location of each user the system makes a distinction between users and associates their location in the real world in coordination with the virtual model.

4.2. VIRTUAL TO PHYSICAL

The common parametric design approaches associate digital parameters with virtual data sources or simulated data. The presence of parametric design is limited to virtual world and the parameters are not usually exposed to the physical world. In order to support collaborative design, a parametric model can be extended with ambient computing, physical parameterization, and interaction. It supports an activity that we refer to as form fostering which integrates form-making and form finding of the ambient and interactive parametric models, with the aim to support collaborative design (Salim et al., 2010b).

Processing multimedia programming is powerful platform in order to model responsive behaviours. Digital representation of the model could be done in both in processing itself or in the programs specially design for that purpose such as grasshopper. Likewise, the physical representation is through the Arduino micro controller connected to processing. Thus, physical and virtual models are developed in parallel and evaluated in a different scale, given that the data source can be simultaneously linked to various representations in both worlds by using Processing, Grasshopper, Arduino as a bridge.

Grasshopper is connected to the Arduino through firefly plug-in. Firefly is a set of software tools which allows near real-time data flow between Grass-hopper and the Arduino micro-controller. In this respect the keywords found in the twitter account, sunny and shady, are associated with a binary value (True_False) in grasshopper. The binary values are the translation of a mechanical system which opens and closes the shading device. This mechanism is based on the rotation of some electrical motors which rotate from 0 to 180 angles. This also control the angle of servos from (0 to 180) which opens and closes the hexagonal shaped modules for example once the user tweets the sunny keyword, the binary key sets on the true value and that changes the angle of servos to zero which closes the hexagonal shading modules. Likewise, when the user tweets shady, that sets the binary key on the false value and rotates servos 180 degree which closes the associated module.

4.3. ANALYTICAL SIMULATION-FEEDBACK LOOP

Focusing on the setup of a responsive system that relies on its own internal feedback processes to trigger a formal change in its components- in accordance with the climatic information received from the external environment- allows a more refined approach to the information transfer between a specific system and its influencing environment.

Through a similar process, using Revit Python Shell, Grasshopper is linked to Vasari in real-time. Project Vasari provides a series of analytical simulations of the parametric 3d model taken from grasshopper and based on the local climate data. The communication between these two platforms benefits from the rapid generative of a parametric model and analytical simulations to examine the performance of the system. Vasari puts the model in a wind tunnel (Figure 5) to simulate how the model reacts to the fluid dynamics and also gives a simulation of solar radiation on the canopy. Since the modules are dynamic and the form of the canopy changes over time, this simulation analysis gives a thorough understanding of how model is responding to the environmental conditions based on the user interaction. The feedback to the system occurs at this point as users

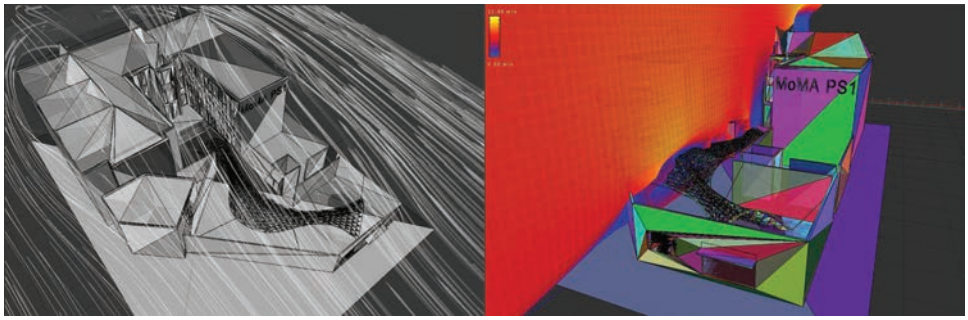

Figure 5. Wind tunnel simulation (2d, 3d simulation in Vasari).

monitor this analytical simulation and will understand how their data input is affecting the form of the canopy and how these changes relate to the wind and solar energy. Thus its design could be considered as an experimental and educational platform to aware users of how architecture should react to weather conditions.

5. Conclusion

The paper demonstrates that architectural system can act as a medium be-tween user intentions and environmental conditions. The collective intelligence of the users can manipulate the form of the canopy which finally will be optimized based on their own needs. Therefore, there is no pre-anticipation of how the form might be optimized, instead it is the users who decide. This project is an example of that shows parametric modelling can be further enhanced for design collaboration by integrating social networks and ambient information. The synthetic system of architecture, informed by users and environmental conditions supports performance for continuously improved spatial conditions through regulation of daylight, radiation exposure, the enclosure of spaces and a diverse visual expression achieved through interaction of the canopy with users and local climate data input.

The continuous research thus attempts to construct simpler, even more de-fined performative methods and prototypes, whose objectives remain to explore structural, phenomenological, social and environmental aspects.

In doing so, future prototypes and models are developed within a described operational framework for response architectural typologies, with focus on ‘Coupled Direct Response’. This approach is based upon integration of data flow from users and environmental condition into one platform.

References

D'Estree Sterk, T: 2006, Responsive Architecture: User-Centered Interactions, *in* K. Oosterhuis and L. Feireiss (eds.), *Game Set and Match II: The Architecture Co-laboratory on Computer Games, Advanced Geometries, and Digital Technologies*, Episode, Rotterdam, The Netherlands.

Eastman, C.: 1972, Adaptive-conditional Architecture, Design Participation, *Proceedings of the Design Research Society's Conference*, Academy Edition, Manchester, UK.

Freidman, Y.: 1972, Information Processes for Participatory Design, Design Participation, *Proceedings of the Design Research Society's Conference*, Academy Edition, Manchester, UK.

Haque, U.: 2006, Architecture, interaction, systems, *Arquitetura & Urbanismo*, **149**.

Hensel, M. and Menges, A.: 2006, Differentiation and Performance-Multi performative Architectures and Modulated Environments, *in* M. Hensel, A. Menges and M. Weinstock (eds.), *Techniques and Technologies in Morphogenetic Design*, AD Wiley Academy, 60–69.

Jaskiewicz, T.: 2010, (In:)forming Interactive Architectural Systems, Case of the XMAiA Meta-model, *Proceedings of the 30th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, New York.

Mitchell, W. J.: 1997, *City of Bits: Space, Place and the Infobahn*, MIT Press, Cambridge, MA.

Mondana, F., Pettinaro, G., Guignard, A., Kwee, I., Floreano, D., Deneubourg, J., Nolfi, S., Gambardella, L. and Dorigo, M: 2004, Swarm-Bot: A New Distributed Robotic Concept, *Autonomous Robots*, **17**(2), 193-221.

Oosterhuis, K.: 2001, *Architecture Goes Wild: Manifest Writings*, 010 Uitgeverij, Rotterdam, The Netherlands.

Oosterhuis, K. and Xia, X: 2007, *iA #1*, Episode, Rotterdam, The Netherlands.

Pasold, A. and I. Foged: 2010, Performative Responsive Architecture Powered by Climate, *Proceedings of the 30th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, New York.

Russell, S. J. and Norving, P: 2009, *Artificial Intelligence: A Modern Approach*, Prentice Hall.

Salim, F. D., Mulder, H. and Jaworski, P.: 2010a, Demonstration of an Open Platform for Tan-gible and Social Interactions with Responsive Models, *Proceedings of the 30th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, New York.

Salim, F. D., Mulder, H. and Burry, J.: 2010b, A System for Form Fostering: Parametric Modelling of Responsive Forms in Mixed Reality, *Proceedings of the Computer Design Aided Architectural Design Research in Asia (CAADRIA) 2010*, Hong Kong, China.

Sherbini, K. and Krawczyk, R.: 2004, Overview of intelligent architecture, *1st ASCAAD International Conference, e-Design in Architecture*, KFUPM, Dhahran, Saudi Arabia.

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OPEN UP THE BUILDING

Architectural relevance of building-users and their participations

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Abstract. As buildings have become more advanced and complex, our ability to understand how they are operated and managed has diminished. Modern technologies have given us systems to look after us but it appears to have taken away our say in how we like our environment to be managed. The aim of this paper is to discuss our research concerning spaces that are sensitive to changing needs and allow building-users to have a certain level of freedom to understand and control their environment. We discuss why, what we call the Active Layer, is needed in modern buildings; how building inhabitants are to interact with it; and the development of interface prototypes to test consequences of having the Active Layer in our environment.

Keywords. Active layer; participation; sensors; interface; BIM; BMS.

1. Introduction

Architects generally design spaces for people to live and work in. Some spaces are designed for specific and well-defined needs while other spaces are more open and designed to cater to unknown needs or for not well-defined groups of people that may change routinely or periodically over time. The aim of this paper is to discuss our research concerning spaces that are sensitive to changing needs and that allow building-users to learn and take control of their own environments.

Lynch (1958) discussed that environments could be designed to 1) offer wide range of choice, 2) be plastic, or 3) be adaptive to provide flexibility for future change. While his main interest was to discuss benefits of environments that can continue to adapt as requirement changes over time, our key interest is to investigate how an environment can be plastic in a relatively short period of time. To be more specific, our interest is in how building-users can actively participate in customising and fine-tuning their environments to their liking in a fluid and

interactive manner. This paper addresses three key issues that prevent building-users from becoming active participants of their environment.

The *first* issue is that the building information which modern buildings hold is largely inaccessible and invisible to their occupants. Although many of them are monitored by an array of sensors, the information generated by them is typically kept for the facilities management (FM) experts. Either the building information model (BIM) and/or building management systems (BMS) hold all necessary data but there is, typically, no interface that allows the occupants to access and decipher the information held. An explanation of BIM, its history and development is given by Eastman et al. (2011). There are various types of information that can benefit and educate occupants to use their environment more effectively and comfortably but our study identified that there is little research conducted to investigate how it can be opened up for the benefit of them. BMS is not open to building occupants because they are not designed to be handled by building-users but we speculate both managers and occupants will greatly benefit from a certain level of open access if it were available in the right way.

The *second* issue is that information held by BIM or BMS does not necessarily bring much benefit to building occupants if the means for them to access the information were not designed specifically for them. The building information available for experts is not necessarily useful for untrained users. Understanding the information about their building and responding appropriately and effectively without causing problems is very likely to be a challenge for most of them. As identified by Brown and Cole (2009), modern and so-called green buildings offer higher availability of personal controls but often, users are not capable of understanding or are not informed of the state of their building or how it works despite their interest to operate their building. We propose this issue can be addressed by providing appropriate user-interfaces for the systems as well as a layer of additional infrastructure. Our current research focuses mainly on how information could be open to users, how they could recognise useful information about their environments in real-time and how they could respond or take action to fine-tune the environment or to plan future changes.

The *third* issue is that the action taken by building-users could conflict with the FM strategies. Building-users should, therefore, be given tools and systems developed specifically for them to take action if they were to be given the access and control of their building information and systems. We propose the Active Layer would be needed to allow building-users and FM to coexist and collaborate effectively to achieve the maximum building performance and satisfaction for both parties.

The following sections provide the background of the relationship of building-users and their building; how they could be accessing data and making decisions

in response to the information that interfaces could provide; the prototype we developed to test the principle of the Active Layer; followed by discussion and conclusion.

2. Background

2.1. PERSONAL CONTROL AND PERCEIVED WELL-BEING

A colleague mentioned that when she was a child living in an older Queenslander house of vernacular tradition, they understood that when it rained heavily they had to close the wooden shutters to prevent the rain from coming into the house. But it would get quite hot and stuffy so they would be aware that immediately after the storm had passed, they would quickly open the windows to allow the cooler air in to make the indoor spaces more tolerable.

We are no longer required to listen for the rain to stop so we can open the windows to adjust our personal environment for thermal comfort. In fact, many of us do not know when the rain stops outside our office space or how to adjust our personal space or if there are devices in place for us to activate that. Having devices that inform us of our surroundings could raise our awareness of how our actions could increase or decrease energy or water usage and in turn affect our planet. We may not need to open windows but we can have open systems that enable us to engage with our environment.

For the past decade, researchers of thermal comfort in building environments have demonstrated in several experiments that users of spaces want to be able to manipulate their environment to suit their personal preferences. The occupants' desire for local control of their immediate surroundings has been exemplified in what has been termed the need for an "operable window". Bordass (1990, p.1) quotes observations by psychologists that the operable window "is disproportionately significant to perceived well-being" and confirms that "people are more forgiving of discomfort if they have some effective means of control over alleviating it" (Leaman and Bordass, 1999, p. 22).

2.2. PERSONAL VS. CENTRAL CONTROL

However, conflicts arise when users want to modify their personal space in a building that is designed to give indoor environment controls to FM. FM needs to run a building efficiently and the BMS controls they are given are usually designed to suit a centrally run system. Even if users were given some say in controlling their particular environment, the BMS information is too complex to be manipulated by untrained users. But having control also means allowing "systems

to operate efficiently according to need" (Bordass and Adrian, 1997, p.7) and this can also mean allowing systems to be more open which may be a key to better building performance and occupant satisfaction.

2.3. FEEDBACK LOOPS AND ACTIVE PARTICIPANTS

From their experiments, Brager claims that "it is critical that buildings be designed so that occupants can be active participants in the indoor climate feedback loop, not simply passive recipients of whatever thermal conditions the BMS delivers" (Brager et al., 2004, p. 32)

One of the necessary steps for better interaction between building-users and building systems is to provide a means for the building information to be easily interpreted by the users. Users could be more knowledgeable building-users if they were given means to understand:

- how the building information given is affecting them personally and
- how their personal adjustment of the BMS will affect others around them (community of users) and also
- how they can affect the overall building conditions (bigger climate change picture).

One of the recommendations from a pilot project done at Queensland University of Technology on thermostat settings and institutional offices is to enable better communication between end users of the building and the building systems themselves. The study found "end-users who have a better understanding of how thermal comfort can be achieved in their space i.e. via timers or individual expectations/adjustments can attain greater satisfaction and productivity with the work space" (Kennedy et al., 2007, p. 65).

Feedback loops enable systems to become more transparent. They open up our understanding and enable us to actively participate in the making of the space to suit our needs. However, in order for this system to work and not just be another non-actionable digital readout, the "feedback on the consequences of exerting environmental control should be directly observable, inherently legible, and deal explicitly with the inhabitants' experience" and not "through add-ons such as orientation sessions, signage, lobby displays etc. which may not be adequate or effective" (Brown and Cole, 2009, p. 244).

2.4. NEED INTERPRETATION AND ACTION - NOT JUST INFORMATION TO ACT

Communication from building systems is still not of great use unless the users understand how to interpret and act on it. When users are given this "interactive

adaptivity" (Cole et al., 2008, p. 333) between themselves and a complex building system that is dynamic and responsive to their participation, then we have opened up the building system. We think that an open system occurs when users understand the information given to them and can easily associate their actions to a desired outcome and also can understand the consequences of their adjustments affecting others around. With our interactions, then we are no longer a passive object of the environment but can be a knowledgeable subject able to manipulate our spaces to suit our requirements quickly and easily.

3. Participatory Building Management

3.1. OPENING UP BUILDING INFORMATION

Making building information simply available does not allow building-users to make informed decisions. This is especially true if the only information available is a set of (raw) data that could only be read or analysed with interfaces designed for experts such as designers, engineers and facility managers. In order for the data to become meaningful and useful for building-users, a set of user interfaces developed specifically for non-experts is essential so that they could more effectively and easily fine-tune their environment for their own benefit. We developed a set of input and output interface ideas and ad-hoc network infrastructure to be retrofitted to our existing environment. We call this the Active Layer.

To investigate these issues in tangible manners, we constructed sensor modules to monitor our environment; software that uploads data to a free online database called Cosm (www.cosm.com); software that downloads the data and overlays the data to BIM; and BIM viewer that provides high-fidelity information for general users to study and learn about their environment. We also constructed a range of ambient displays and feedback systems that respond to user interactions and/or environmental conditions according to certain (predefined) parameters. Further information of this could be found in our recent paper (Santo, 2012).

3.2. AMBIENT BUILDING INFORMATION

Just as people look through a window to stay informed about their local climate information in real time, we aim to provide the ambient information that keeps building-users informed about their local environment and the building performance. As McCullough (2004) argues that digital computing tends to augment architecture, rather than replace it, the Active Layer is to augment existing or newly designed environments to allow building-users to take active roles in managing their spaces.

Wigley (2007, p. 52) claimed “the architectural responsibility to house humanity became a responsibility to shape flows of information”. We are critical about how modern buildings no longer allow us to stay in touch with flows of information. Our aim, therefore, is to reintroduce the level of understanding and control we used to have with simple buildings in the past. With this in mind, we first chose to investigate how ambient information could be introduced to our spaces to keep us informed about the flow of information. The provision of ambient information to our environment through (tangible) interfaces is nothing new as research has been conducted since the 90’s (see Ishii and Ullmer, 1997). Fair amount of research has been conducted on the benefit of ambient information to positively influence user behaviours in their environment. This was best demonstrated by Pousman and Stasko (2006). Our contribution is that we are aiming to construct a layer that consists of network infrastructure and various devices that are integrated into BMS through BIM.

Our current interests are in the thermal, luminous and visual comfort of building-users, the consequent energy savings and the level of user engagement and satisfaction that our interface prototypes can monitor and communicate. The ambient interfaces that constitute a part of the Active Layer is for engaging building-users to be positively critical about their environment and for them to respond actively to fix it. Figure 1 shows some of the available ambient interfaces that we have constructed (see Loh and Santo, 2010, and Santo, 2012, for further descriptions) that can be used to show certain aspects of the building’s environment. The majority of users do not need to accurately interpret detailed information before they can understand the need or method to effect a change in their environment. They need only be provided with a level of information sufficient for them to

Figure 1. Ambient interface prototypes networked as devices for Active Layer.

sense this requirement and this can be communicated through ambient interfaces. Thus, complex building information can be distilled and visualised understood by the user through moving objects and changing intensity and/or colour of lights (typically LEDs).

3.3. HIGH-FIDELITY BULDING INFORMATION

While ambient information can keep building-users informed about their otherwise invisible environment, further resolution of information is often needed to take informed actions. This is especially true for building-users who are keen to participate and contribute to the extent that they would take an active part in maintaining and improving their own environment.

Typically, building-users in most office buildings need to come into contact with FM when they want to or are interested to:

- alter the indoor climate (the temperature, humidity, lighting levels),
- alter or determine the use of spaces (space allocation, event planning, etc.),
- report building problems (plumbing, electrical lighting, etc.),
- provide feedback for development and renovations.

Each of these actions can benefit from having intuitive and informative interfaces that allow users to determine the use and condition of their environment by themselves. The interfaces implemented utilise BIM, by targeting objects within the model and associating the data streaming from these ‘real’ sensors to the ‘virtual’ objects held in BIM.

BIM virtually always holds a geometric representation as well as attributes and meta-data of objects and the project. With the level of information BIM is designed to hold, it is an ideal platform to visualise easily graspable yet detailed information of the building for its users if a BIM viewer is designed specifically for them. To develop a means to obtain finer and localised environmental information, we constructed a sensor module that monitors light, temperature, humidity and sound of its immediate environment (Figure 2a). Figure 2b shows a possible appearance of the sensor module that can be moved around by the users. As the Internet access became ubiquitous for many, providing platforms to visualise BIM tailored specifically for building-users, as shown in Figure 2c and 2d, has become trivial.

In our preliminary experiments, we implemented an interface to allow building-users (primarily ourselves) to visualise environmental data as it was streamed to the online server. While ambient interfaces allows us to visually perceive current conditions, observe changes that are normally invisible, and gain certain level of awareness; these computer user interfaces built around BIM could offer high-

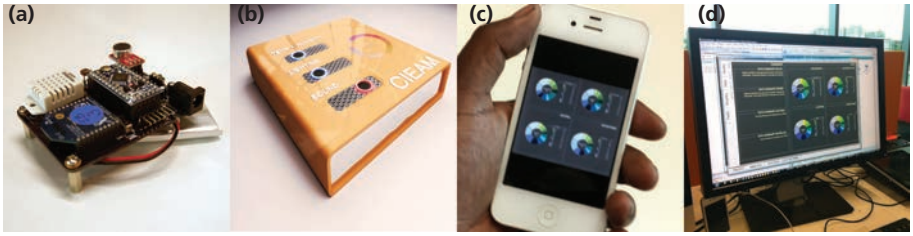

Figure 2 (a, b, c and d). Personal sensor modules and screen interfaces.

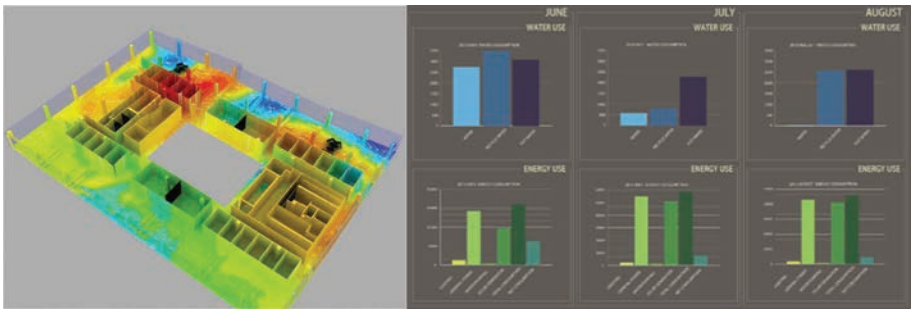

Figure 3. Dashboard interfaces for high-fidelity building information.

fidelity information and accurate analysis for building users to take informed actions. Figure 3 shows possible temperature distribution in our office floor and further information. A building-user may study this and choose to move to a hot-desk that matches better to their personal needs. High-fidelity information could ultimately allow building-users to stay in touch with flows of information and them to access further information to look for better alternative possibilities. We speculate that this could engage some building-users to a level comparative to those who look after their gardens with dedication and so some people who eagerly customise their computers and smart-phones. With the introduction of the Active Layer, we argue that the environment in their building becomes theirs.

4. Discussion

The use of BIM by FM and other experts as the means to visualise information has been explored by some researchers (Babsail and Dong, 2006; Liu and Akinci, 2009). Our approach to extend the use of BIM to all building-users however, is unique. Combined with the range of interfaces that provide ambient information for keeping users in touch with their environment, we speculate it is possible to

organise and maintain a community of building-users to become the effective agency, along with FM, for managing and maintaining their building. The Active Layer could ultimately allow designers and engineers to design buildings that are beyond what the current BMS and FM could effectively manage. The principle could apply to all buildings regardless of whether they had technologically advanced systems that would require advanced BMS and trained experts, or highly sophisticated passive systems that would require cooperation by building-users.

Our ultimate aim is to convert building-users who currently are the "passive recipients of the outcomes of" environments created by designers and researchers (Cole et al., 2008, p. 325), into active participants who will be responsible for the operation of their own environment. This research was conducted largely in interpretive methods (Swann, 2002) where we came up with quick assumptions or hypotheses, constructed hardware and software to test solutions quickly in an ad-hoc manner within our own spaces and evaluated the consequences. All issues discussed in this paper were examined with iterative collaboration process. The research reported in this paper remains relatively personal and it does not intend to provide any effective or measurable solution. The focus instead has been to make contributions by suggesting opportunities and possibilities in technologically enhanced environments, directions for possible future research for us as well as others, and sharing our investigation and methods of constructing hardware and software systems.

We are currently in discussion with FM and other stakeholders to gain access to the BMS of our building that was completed in November 2012. The next research goal is to study the implications of the Active Layer with a wider community of building-users rather than just about 10 researchers (us) discussing it amongst ourselves in a highly experimental and an ad-hoc manner.

5. Conclusion

There is, currently, little means for building-users to actively transform their environment to their liking. Our study proposes that we could give them the means to interact with their building environment with as much ease and intimacy that we used to have with our older simpler buildings. We propose this means can be successfully implemented with the use of the Active Layer. Through a series of interfaces that provide low (ambient) and high fidelity information, the Active Layer provides the means for building-users to access building information that would normally be beyond their comprehension and reach. So through this interaction, building-users are able to become active participants of their environment.

References

Babsail, M. and Dong, A.: 2006, Sensor-based Aware Environment, *ASCAAD Computing in Architecture / Re-Thinking the Discourse*, ASCAAD, Sharjah, UAE.

Bordass, B.: 1990, The Balance Between Central and Local Control Systems, *Environmental Quality 90 Conference*.

Bordass, B. and Adrian, L.: 1997, From Feedback to Strategy, *Building in Use '97*.

Brager, G. S., Paliaga, G. and De Dear, R.: 2004, Operable windows, personal control, and occupant comfort, *ASHRAE Transactions*, **110**(2), 17–35.

Brown, Z. and Cole, R.J.: 2009, Influence of occupants' knowledge on comfort expectations and behaviour, *Building Research & Information*, **37**(3), 227–245.

Cole, R. J., Robinson, J., Brown, Z. and O'Shea, M.: 2008, Re-contextualizing the notion of comfort, *Building Research & Information*, **36**(4), 323-336.

Eastman, C., Teicholz, P., Sacks, R. and Liston, K.: 2011, *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, John Wiley.

Ishii, H. and Ullmer, B.: 1997, Tangible bits: towards seamless interfaces between people, bits and atoms, *CHI'97 Proceedings of the SIGCHI conference on human factors in computing systems*, ACM, New York, 234–241.

Kennedy, R. J., Loh, S., Miller, W. F., Summerville, J. A. and Heffernan, M. E.: 2007, Same Latitude New Attitude: Reducing Greenhouse gas emissions in institional offices through positive adjustment of thermostat settings, *Australian Institute of Refrigeration, Air Conditioning and Heating Pre-loved Buildings Conference: Continuing the Push*, Brisbane, Australia.

Leaman, A. and Bordass, B.: 1999, Productivity in buildings: the "killer" variables, *Building Research & Information*, **27**(1), 4–19.

Liu, X. and Akinci, B.: 2009, Requirements and Evaluation of Standards for Integration of Sensor Data with Building Information Models, *Computing in Civil Engineering*, ASCE, 95–104.

Loh, S. and Santo, Y.: 2010, Please touch the plant on your way up the stairs..., *OZCHI '10 Proceedings of the 22nd Conference of the Computer-Human Interaction Special Interest Group of Australia on Computer-Human Interaction*, ACM, New York, 412–413.

Lynch, K.: 1958, Environmental Adaptability, *Journal of the American Institute of Planners*, **24**(1), 16–24.

McCullough, M.: 2004, *Digital ground: architecture, pervasive computing, and environmental knowing*, MIT, Cambridge, MA.

Pousman, Z. and Stasko, J.: 2006, A taxonomy of ambient information systems: four patterns of design, *AVI'06 Proceedings of the working conference on Advanced visual interfaces*, ACM, New York, 67–74.

Santo, Y.: 2012, An interactive and adaptive building layer: strategies for allowing people to become advanced building-users, *OzCHI '12: Proceedings of the 24th Australian Computer-Human Interaction Conference*, ACM, New York, 521–529.

Swann, C.: 2002, Action research and the practice of design, *Design Issues*, **18**(1), 49–61.

Wigley, M.: 2007, The architectural brain, *in* A. Burke and T. Tierney (eds.), *Network practices: new strategies in architecture and design*, Princeton Architectural, New York, 30–53.

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MODELLING, SIMULATION AND VERIFICATION OF PNEUMATICALLY ACTUATED AUXETIC SYSTEMS

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Abstract. This paper presents the development of an SLS 3D printed auxetic structure actuated to a predefined form by an embedded pneumatic network through an iterative process of feedback between digital simulation and physical testing. This feedback process is critical to the development of a more accurate predictive model, and to compose the geometry of the suggested structure. An approach based on the emergence of the final structure from the convergence of the behaviour of sub – structures and a methodology based on the analysis and synthesis of the simplest sub-system is the core of this research. The results indicate a promising simulation environment and a novel methodology for the design and fabrication of auxetic structures with embedded pneumatic actuation. This exploratory research suggests a fertile space for investigation within the field of adaptive architecture and soft kinetic design.

Keywords. Auxetic; fabrication; simulation; pneumatic; kinetic.

1. Introduction

Today kinetic architecture is understood as a response to technological, economical and social change (Kronenburg, 2007) and its role is extended to the creation of an architectural artefact able to adapt to human needs and environmental changes. Although the theoretical approach to kinetic architecture promotes the benefits of dynamic environments, its physical application is still less developed (Hoberman, 2011) due to the limited options for kinetic systems. For the purpose of this research, it is suggested that the categorization of kinetic systems in relation to their technological and behavioural characteristics be made in two groups: hard and soft systems. The first group, the hard system, which is more developed, refers to structures of which the function and design relies on rotational nodes and rigid links (trusses, pin joined, tensegrity), and they are made of many components. They have many disadvantages like heavy weight, a large number of components, many assemblies, rigid movements, high-energy consumption, and they need very complex computation to

control their movements (Pfeifer et al., 2012). On the other hand, the less developed soft kinetic structures with soft behaviour are promising as they use smartness in their composition to simplify movements, and eliminate computation processes during control. Furthermore soft kinetic systems, due to their intrinsic compliance, can safely interact with humans as it is stated in *"Festo Bionic Handling Assistant"* (Pfeifer et al., 2012). In addition with digital-driven fabrication and design technologies they can be optimised, simulated and manufactured to adapt to specific conditions.

Accordingly the motivation for this research lies in designing and creating a morphing compliant auxetic structure, actuated from an embedded pneumatic network, and fabricated with additive layer manufacturing as a design opportunity for use in soft kinetic architecture. Therefore it is suggested to synthesize the geometry of the structure using a re-entrant unit cell, and subsequently to define in what extends the geometry of the cell, that it is related to the behaviour of the structure. Finally the proposed simulation environment is able to predict the overall behaviour in relation to the geometry of the unit cell, which is based on Direct Stiffness Method and on an algorithm that creates and solves hierarchies between the sub-systems.

2. Background

Auxetic structures have a negative Poisson ratio and an inverse elastic behaviour (Figure 1), which exhibit interesting mechanical properties of which the more intrinsic for an architect is their ability to form synclastic surfaces. Evans argues that by varying the cell geometry of auxetics it is possible to produce different combinations of curvatures (Evans, 1991). This argument forms the basis of the research held in this paper as it explores how the variations of cell geometry affect the behaviour of the suggested structure, of which the geometry is based on the basic unit cell as introduced by Masters and Evans (1996).

The geometry of the unit cell (Figure 1) leads to the hypothesis that its repetition could form bellows. Through the studies of bellows, it has been suggested that the optimisation of the behaviour of the structure could be done by changing the length of the incident edges of the two vertices pointing 'inward,' or towards the interior of the polygon of the unit cell, as it is described in Figures 2–3. By adjusting the length of the edges L_1 and L_2, (Figure 2) it will differentiate the compliance behaviour between the upper and lower sides of the structure, and in this way compelling the prototype to bend by preventing its uniform linear elongation.

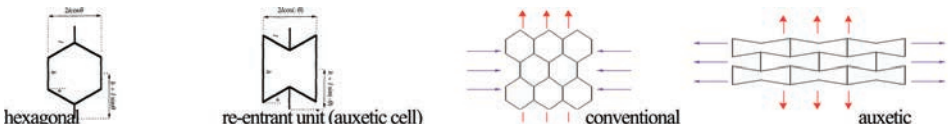

Figure 1. Re-entrant cell proposed by Masters and Evans (1996).

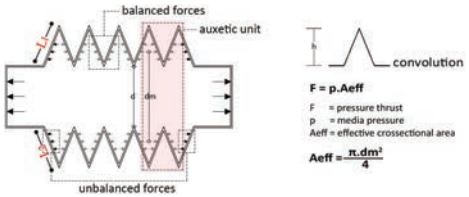

Figure 2. Diagram of the engineering physics of bellow according to Hyspan (2005).

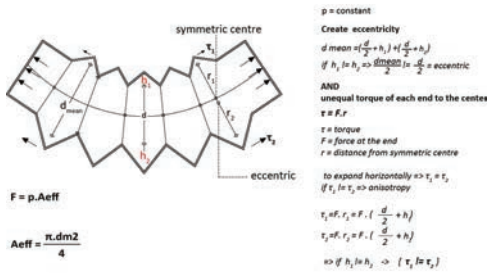

Figure 3. Diagram of the engineering physics of bending bellow.

While the internal pressure is known and is homogeneous, it is proved from the equation of pressure/thrust that in order to create eccentricity it should be changed the **A**eff (Figure 2), and therefore the ratio of h1 divided by h2 should not be equal to one, as it is explained in the diagram below (Figure 3).

There are many methods to digitally study the deformation of a structure (Kaminakis & Stavroulakis, 2012), and most of them are related to numerical methods and non-linear analysis (Kirk, 2001), particularly in the case of Real Time Deformations (RTD). However in this research it is suggested that RTD can be solved by analytical methods, specifically using the Direct Stiffness Method based on Felippa's book (2004).

3. Research Method

To begin, 3D printed (SLS) bellows—which are known examples of compliant mechanisms based on the selected auxetic cell, and which are actuated from internal pneumatic forces—were tested to determine what extent those structures can be formed and still function. Having achieved satisfactory results during the initial tests, the next step was to develop the simulation environment using the finite element method, informed from observations gained after the juxtaposition of the 3D scanned (Xbox Kinect Camera) physical prototype to the digital one.

3.1. FIRST MATHEMATICAL MODEL OF BELLOW STRUCTURE

The first mathematical model derived from the studies of the auxetic cell. It was suggested that it could be translated into a mathematical representation based on pin-joined trusses, while the internal pressure could be represented as forces – vectors acting on nodes (Figure 4), and that it could be solved by an algorithm based on the Direct Stiffness Method. Therefore the first simulation algorithm has been developed as a pin-joined continuous mathematical model, and after an optimisation of its stiffness by adjusting the elasticity of its trusses, its adequacy has been tested.

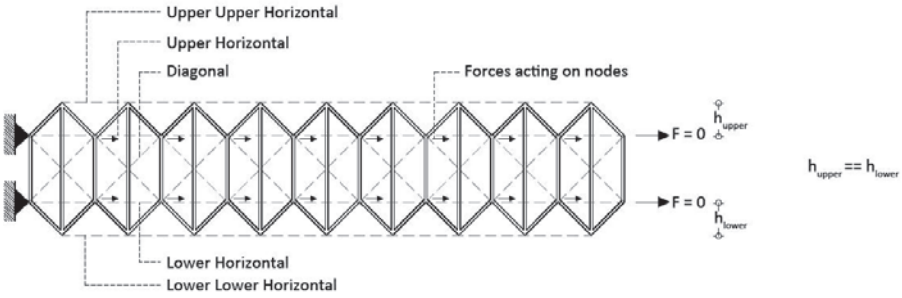

Figure 4. Behaviour of mathematical model of continuous 2D bellows structure during simulations.

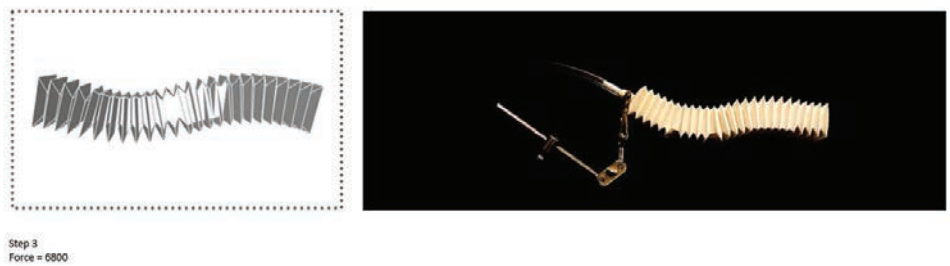

Figure 5. Physical and digital prototypes of anisotropic bellow during tests.

The test required a manual alteration to the mathematical model and the geometry of the auxetic unit in order to achieve an anisotropic deformation (Figure 5). Having achieved the proposed shape shift in the digital model it has been 3D printed and its physical artefact tested. The high correlation of their behaviours (juxtaposition of the 3D scanned model with the digital) lead to the conclusion that by changing the geometry of every unit cell it was possible to force a bellow to bend, while the mean curvature of bending is proportional to the ratio of the heights of the auxetic unit (Figure 5). Furthermore it is also concluded that it is possible to simulate the behaviour of a bellow using a continuous pin-joined mathematical model and DSM.

3.2. MATHEMATICAL MODEL AND FIRST ALGORITHM OF AUXETIC STRUCTURES

Having achieved adequate results in the previous experiments, the next step was to test its performance in auxetic based structures following an inverse procedure. Using the knowledge gained in previous experiments, digital analysis and synthesis of the geometry prior to the fabrication and test of the physical artefacts was attempted.

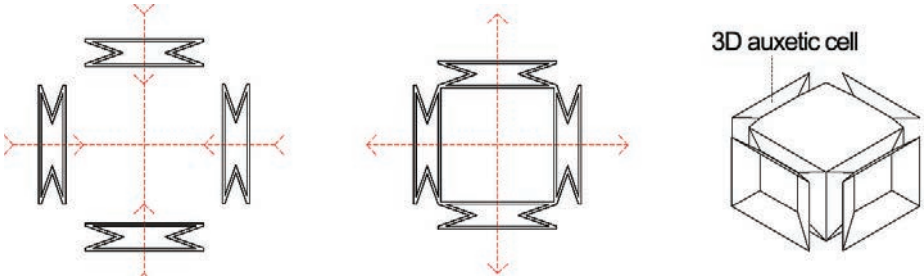

Figure 6. Hypothesis of geometry of cellular auxetic structure.

Specifically it had been suggested that the unit cell of the tested bellows could form auxetic structures in a certain geometrical composition. Thus the following experimental procedure was an attempt to define and simulate a possible digital auxetic geometry based on the properties of bellows. The auxetic unit cell proposed (Figure 6) was a polar array of four bellow auxetic units with 90^o angle offset between them. The final auxetic structure was a rectangular array of those unit cells.

The research led to the development of a three-dimensional digital auxetic model having all possible triangulations in every unit. The model worked in small dimensions and with a small number of cells during the digital tests. When the number of cells increased, the simulation became very slow due to the huge number of equations it had to resolve. The above method of simulation proved insufficient to be used with complicated auxetic structures due to the large size of the resultant stiffness matrix. The fact that a digital simulation environment should be fast and flexible stimulated the introduction of a new hypothesis for the simulation of these kind of structures, which stated that “an algorithmic analysis and synthesis of sub-systems could be the base for the simulation of a complex system using linear analysis”.

3.3. REFORMULATION: ALGORITHM BASED ON SUB-SYSTEMS ANALYSIS

According to the discretization hypothesis, the structure should be separated into subsystems, and the structural behavior of each sub-system should be solved separately following a hierarchical procedure. The direct stiffness method calculates the deformation of a pin-joined structure, which always has some nodes fixed in 2 or 3 directions. The fixed nodes could have prescribed displacements (boundary conditions), which will be calculated while the method is solving the deformation of the structure. The idea behind the discretization, solution, and hierarchical connection relies on this part of the method. It is argued that if the algorithm begins the simulation from one single cell with fixed nodes, other than where the nodes are connected to other elements, and a constant force, the DSM is able to calculate the displacements of the remaining nodes. The second element will have as fixed nodes the nodes

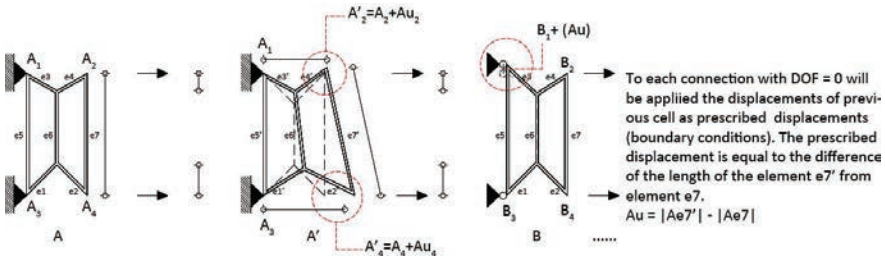

Figure 7. Diagrammatical description of first phase of component based algorithm.

$$\sum_{i=0}^{n}\{\boldsymbol{S}(\boldsymbol{C_i})\} + \{\boldsymbol{S}(\boldsymbol{C_{i+1}} + |\boldsymbol{u_i}|).\boldsymbol{TR_{i+1}}(\vec{\boldsymbol{w}}_i)\} + \ldots + \{\boldsymbol{S}(\boldsymbol{C_n} + |\boldsymbol{u_{n-1}}|).\boldsymbol{TR_n}(\vec{\boldsymbol{w}}_{n-1})\}$$

$\boldsymbol{S}$ = *structural analysis,* $\boldsymbol{C}$ = *component,* $\boldsymbol{u}$ = *prescribed displacements,* $(\boldsymbol{T}+\boldsymbol{R})(\vec{\boldsymbol{w}})$ = *(Transformation) + (Rotation matrix) of unit vector w*

Figure 8. Proposed component based algorithm for bellow structure.

where they are connected to the first element. The known displacements of those nodes from the simulation of the first element will be the prescribed displacements (boundary conditions) for the simulation of the second element. Following this procedure, the algorithm will be able to solve the structural behavior of all the elements. Then applying a transformation matrix to combine the elements together, the algorithm will result in the simulation of the behavior of the whole system (Figure 7 and 8). To test the new hypothesis of the mathematical model it was suggested to test it first in a simpler model (bellow) and in a more complex auxetic structure.

During the second phase of the algorithmic procedure, a rotation matrix R of unit vector ($\overline{w}$) and a transformation T is applied to each element after structural analysis S, in order to combine the digital model in its final shape (connect elements).

The proposed algorithmic method has been successful in simulating the bending. However from the comparison of the curvatures of the two models, the conclusion is derived that the physical bellow has non-linear viscoelastic behaviour, which increases in an amplitude of a sine wave until the middle of the structure as it decreases in amplitude of a cosine wave from the middle to the end of the structure.

From the above observations it was suggested to add viscoelasticity to the mathematical model by changing the magnitude of force in relation to the length of the structure. The proposed force acted along the structure from the beginning to its centre in a sine function, while it decreased from the centre to the end in a cosine function.

After several tests it was determined that the correlated mathematical model was successful in simulating fabricated bellows. From the results, it has been proven that by simplifying the mathematical model, it is possible to simulate quickly and accurately the behaviour of a fabricated pneumatically actuated bellow.

3.4. AUXETIC STRUCTURE: FINAL DIGITAL MODEL AND ALGORITHM

To test the algorithmic process with an auxetic structure, it was suggested that a sub-system geometry derived from the diagonal separation of four sub-elements (Figure 9), which has four auxetic units would be able to transform the component in four directions. The proposed algorithm (Figure 10) for this approach used three types

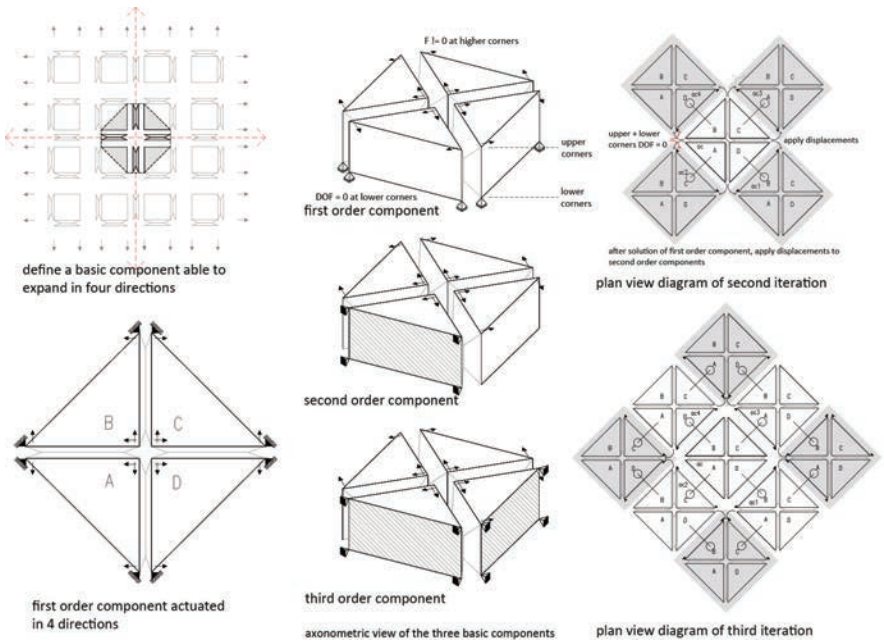

Figure 9. Diagram of the mathematical model and basic steps of final algorithmic process.

$$\sum_{j=1}^{n} j = \{S(C1)\} + \sum_{i=1}^{2^{2*n}} \{S(C2_i + |u1|).TR_i((\vec{w}1)\} + \sum_{i=1}^{4} \left\{ S(C3_i + |u2_{i-1}| + |u2_{i+1}|).TR_i(\frac{\overrightarrow{w2_{i-1} + w2_{i+1}}}{2}) \right\}$$

S = *Structural analysis,* Ck = *Component k,* , uk = *prescribed displacements derived from component k,*

$TR\ (\vec{w})$ = *(Transformation) + (Rotation matrix) of unit vector w*

Figure 10. Final algorithm for the simulation of an auxetic structure.

of components in relation to the hierarchy of connections with their neighbours. The first component C1 had eight rectangular connection-faces (CF) with fixed lower nodes. The second component C2 had four fixed nodes at the upper and lower corners of its rectangular CF, and the third component C3 had two rectangular CF with eight fixed nodes at the upper and lower corners of each face. The first component C1 was positioned in the centre, and was constructed only one time at the beginning. After its structural analysis the displacements of the edges of its CF have been applied as prescribed displacements to the fixed nodes of the CF of the components C2, which had been connected to the four CFs of the component C1. During the third iteration, a component C3 had been positioned between two components C2 after the displacements of the two CF of neighbouring C2s applied to the edges of CFs of C3. The last two steps had been repeated proportional to the size of the auxetic structure.

3.5. RESULTS: DIGITAL MODEL SIMULATION AND PHYSICAL ARTEFACT ACTUATION

According to the measurements the simulation algorithm, and the geometry of structure, proved able to transform the structure and to form synclastic bending (Figure 11) when the ratio of the heights of auxetic units was not equal to one (Figure 3). Therefore it was concluded that the curvature of the structure could be optimised according to the ratio of auxetic units.

Having achieved adequate results with the digital model, its physical artefact was then fabricated. During the tests, the physical prototype exhibited an auxetic behaviour and formed synclastic geometries (Figure 10). The forces acted internally from the pneumatic actuation and produced the expansion of the structure in

Figure 11. Simulation of auxetic based structure in Processing.

Figure 12. Caption of fabricated auxetic structure with three auxetic units per unit cell during actuation.

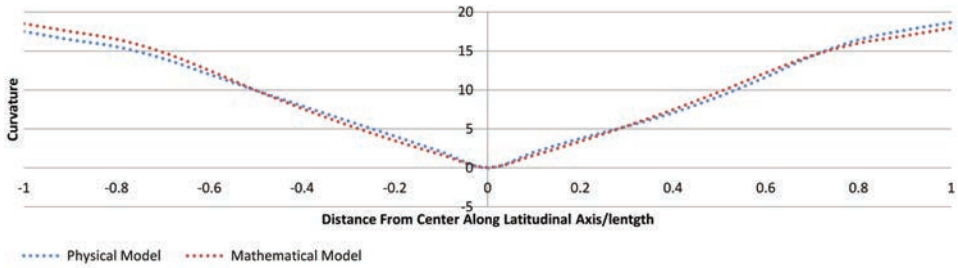

Figure 13. Comparison of curvatures of mathematical and fabricated models with ratio 0.29 along their latitudinal axis.

two perpendicular axles, and therefore have created auxetic behaviour (Figure 12). The fabricated auxetic structure had similar viscoelastic behaviour along its axis with fabricated bellow structures. The application of "viscoelastic force" to the mathematical model also created viscoelastic behaviour and a high degree of correlation (Figure 13).

4. Discussion

The combination of physical and digital models, and the iterative experimenting process, proved adequate in the creation of the hypothetical system, and to the acquisition of its properties in a digital environment. Additionally the discretization of the geometry in simpler units made possible the use of linear analysis for the simulation of the geometry. The final algorithm was responsible for creating hierarchies between unit cells. Starting from a centre cell, which had four links, the geometry expanded by connecting them to four other cells. By applying boundary conditions to the connection nodes, and using translation matrices, the simulation of the behaviour of the structure was achieved.

This research in soft kinetic systems through the optimisation of the geometry of a re-entrant unit cell suggests a further exploration in possible forms and behaviours using other re-entrant geometries. Even though this paper has analysed only a simulation algorithm, it is suggested that it could be the basis of future research into a more sophisticated optimisation algorithm able to prescribe behaviours in fabricated soft kinetic systems. The development of a smart CAD environment able to prescribe behaviours could invigorate the research in methodologies for behavioural design, and a theoretical discussion on form finding through these methods.

5. Conclusion

The methodology based on an iterative process (hypothesis, test and feedback), succeeded to define an adequate method of creating, simulating and optimising the behaviour of an auxetic structure. Following this procedure, both the digital and physical systems were constructed. By understanding and manipulating the micro-behaviours of the auxetic sub-components it was possible to design, optimize and simulate the emergent macro-behaviour of the whole.

The implementation of digital techniques in design, simulation and fabrication of auxetic based pneumatically actuated structures breaks new ground for research in soft kinetic systems in dynamic architecture. Consequently it proposes a research space for fabricated soft kinetic systems with prescribed behaviours able to interact softly with humans and to adapt smartly to the environment.

Acknowledgements

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References

Evans, K.: 1991, The design of doubly curved sandwich panels with honeycomb cores, *Composite Structures*, **17**(2), 95–111.

Felippa, C.: 2004, *Introduction to Finite Element Methods*, Colorado: Department of Aerospace Engineering at Center for Aerospace Structures University of Colorado.

Hoberman, C.: 2011, Adaptive Structures: Building for performance and sustainability, *Proceedings of ACADIA 2011*, 56–59.

"Hyspan": 2005. Available from: Hyspan Precision Products <http://www.hyspan.com/glossary.html/> (accessed 2 July 2012).

Kaminakis, N. and Stavroulakis, G.: 2012. Topology optimization for compliant mechanisms using evolutionary-hybrid algorithms and application to the design of auxetic materials, *Composites Part B: Engineering*, **43**(6), 2655–2668.

Kronenburg, R.: 2007, *Flexible: Architecture that responds to change*, 1st ed. London: Laurence King Publishing LTD.

Kirk, M.: 2001, Non-linear Structural Analysis as Real-Time Animation: Borrowing from the Arcade, *Proceedings of the Computer-Aided Architectural Design Futures 2001 Conference*, Eindhoven, 643–656.

Masters, I. and Evans, K.: 1996, Models for the elastic deformation of honeycombs, *Composite Structures*, **35**(4), 403–422.

Pfeifer, R., Lungarella, M. and Fumiya, L.: 2012, The challenges ahead for bio-inspired 'soft' robotics, *Communications of the ACM*, November, **55**(11), 76–87.

VIRTUAL AND AUGMENTED REALITY

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WHAT IS HAPPENING TO VIRTUAL AND AUGMENTED REALITY APPLIED TO ARCHITECTURE?

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Abstract. This paper presents the results of a comprehensive survey of activities on research and development of Virtual and Augmented Reality applied to architecture. 200 papers were reviewed, taken from annual conferences of the Association for Computer Aided Design In Architecture (ACADIA) and its sibling organizations in Europe (ECAADE and CAAD Futures), Asia (CAADRIA), the Middle East (ASCAAD) and South America (SIGRADI). The papers were grouped in research areas (design method, architectural theory and history, performance evaluation, human interaction, representation and process & management), emphasis (education, application, collaboration, visualization, practice and theory) and technology development stage (specification, development, application demonstration and evaluation). The period of study comprises 11 years, from 2000 to 2011. Findings for each category are described and key publications and authors are identified.

Keywords. Virtual Reality; Augmented Reality; study of activity.

1. Introduction

Virtual Reality (VR) and Augmented Reality (AR) are technologies that add potential benefits from initial planning and conceptual construction design to facility management and operation phases. Moreover, these technologies improve the visualization and interaction of a building or infrastructure design and construction process and also the communication and innovation within projects.

VR is known as a technology that adds the dimensions of immersion and interactivity to three-dimensional computer generated models and offers an exploration that is not viable with the traditional form of representation (Burdea and Coiffet, 2003, p. 2). For the designer in Architecture, Engineering and Construction (AEC), one example of advantage in VR use is when applying virtual reality systems as CAVEs that offer the opportunity for direct perception of the forms and

spaces through immersion inside an imaginary, computer-generated "virtual world", large enough to walk through (Okeil, 2010).

AR can be summarized as a technology that uses VR to add virtual objects to real environments in real-time, using technological devices for the overlapping of images (Azuma, 1997; Höhl, 2009; Kirner et al., 2004). In architecture and construction this technology can assist in the design and visualization of architectural forms, results of simulation and analysis of energy issues as well as in the manufacturing of structural components or directly in the construction, for example, at the construction site or during Post-Occupancy Evaluation (Amin, 2007).

Despite VR and AR potentials there are still difficulties which withhold their use in AEC. According to Kalisperis et al. (2002), even though VR application has increased in general, in architecture professors are not using its potential. If this technology was applied in the early years of undergraduate courses, the status of the student from observer to a real participant in the learning process could be changed. In architecture and engineering practice, difficulties such as costs and need of training for familiarization with unconventional devices (trackers, gloves, glasses) can be adoption limiting aspects. As for AR, the drawback is the fact that most research is still in computer science and there is lack of motivation and funds for applied research (Wang et al., 2008).

Both technologies are now almost 45 years old, what motivates a comprehensive survey of activities on research and development of Virtual and Augmented Reality applied to architecture. In order to understand this context, a study of activity was carried out for the period from 2000 to 2011. 200 papers were reviewed, taken from annual conferences of the Association for Computer Aided Design in Architecture (ACADIA) and its sibling organizations in Europe (ECAADE and CAAD Futures), Asia (CAADRIA), the Middle East (ASCAAD) and South America (SIGRADI). Important, previous research effort have applied data mining techniques to find research patterns in Computer Aided Architectural Design (CAAD) (Chiu et al., 2002) or have developed machine-assisted infrastructure and metrics to explore CAAD corpus (Bhatt and Martens, 2009). Therefore, this study being another comprehensive study on CAAD, considering ACADIA articles, may appear to commit one of the seven deadly sins of CAAD (Maver, 1995), the sin of Déjà vu. However, this study is intended allow knowledge discovery specific to virtual and augmented reality applied to architecture considering specific aspects as: Brazilian architectural graduate program research areas, technology development and research emphasis.

2. Comprehensive Survey of Activity

The survey of activity was developed in the following stages: theme definition, preliminary review, problem formulation, reference source identification, search

plan, reference collection, material booking, reading and filtering, material classification and analysis. The theme definition stage limited the scope of the study where the research question and period of review was posed. The preliminary research involved unstructured search in citation and scientific databases. This first experimental search was driven by the terms Virtual Reality and Augmented Reality, in fields such as abstract, title and keywords; limited to the subject of social science and arts & humanities. The problem formulation stage was dedicated to specifying parameters that would allow a comprehensive survey. Therefore, three aspects were defined: graduate program research areas, research emphasis and technology stage development. Since the study may indicate research trends and voids, Brazilian architectural graduate program research areas were selected so that findings may guide research directions. The Brazilian agency for Coordination of Improvement for Higher Education (CAPES) which is a government organization that plays a key role in the expansion and consolidation of graduate studies in the country was selected for areas of research definition. Therefore, the areas of research in architecture were defined as: design method, architectural theory and history, performance evaluation, human interaction, representation and process & management. Still in the problem formulation stage, considering results from the preliminary research, it was observed that studies in VR/AR applied in architecture presented specific emphasis. The emphasis observed were in: education, application, collaboration, visualization, practice and theoretical discussion. Finally, since VR and AR are intrinsically related to technology: software, hardware and communication, the stages of maturation as specification, development, implementation, demonstration and evaluation were also defined for observation.

In the stage of reference source identification the journals International Journal of Architectural Computing, Virtual Reality, Automation in Construction and the Cumulative Index of Computer Aided Architectural Design (CUMINCAD) were selected in order to represent sources where peer review articles related to architecture, computer science and engineering could be found. Since initial article samples were not homogenous in time and size, the digital library (CUMINCAD) was chosen in order to drive sample study to proceeding papers, with architectural emphasis.

The survey sample resulted from searching works with the phrase virtual reality and/or augmented reality in articles´ title or abstract. References were exported to the online bibliographic database ENDNOTE WEB in order to organize, treat and manipulate. The abstracts of collected papers were read and classified considering the comprehensive parameters defined. This process resulted in the material classification. Once classified the analysis took place by developing publication distribution in function of time, quantification of publication in

comprehensive parameters and extraction of findings examples from full paper. The period of survey comprised 11 years, from 2000 to 2011.

3. Comprehensive Parameters

3.1. RESEARCH AREAS

It was observed that the research areas interested in VR and AR applied to architecture are design methods, architectural theory and history and performance evaluation (Figure 1). Research on VR and AR alone in Human interaction, representation and process & management was observed in smaller percentage. However, there is an integration of these last three areas with design method.

Design Method was addressed by 46% of the articles. Methods present the use of these technologies taking place in different phases of the design in addition to being applied in different ways during the process. An example is the method of exchanging ideas between members of multidisciplinary teams in early design development assisted by VR/AR. Analysis of cities, in digital models, are supported by these technologies in order to promote the development of standards and guidelines during creation of city models (Boudakis, 2001).

Theory, history and architectural critique are cited in 23% of articles. Ahmad Rafi and Karboulonis (2000) theorize on the dichotomy between art and science related to design creativity throughout time and point out that improvements in design solutions are necessary when adopting new technologies to provide effective visualization and communication of ideas and concepts.

20% of researched articles focused on human interaction with the space and artefacts (considering ergonomics and perception). This subject is shown in

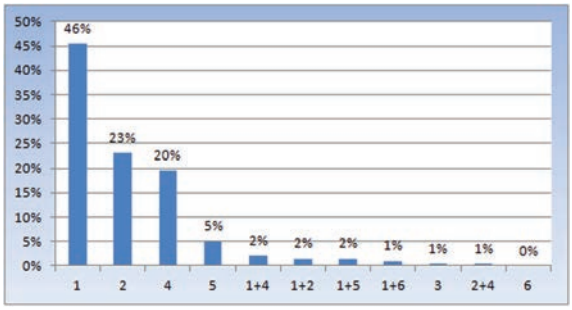

Figure 1. Distribution of publications according to the research areas of: (1) Design method, (2) Architectural theory and history, (3) Performance evaluation, (4) Human interaction with space and artefacts, (5) Representation, (6) Process & management.

Guimarães (2007) where user perception of Information and Orientation Systems using different VR technologies was compared with traditional in loco system.

3.2. EMPHASES

The most observed studies emphases were on how to apply VR and AR, with focus on how to use them for visualization and how to use in practice (Figure 2). Other highlights consist in studies that emphasize VR and AR applied to education.

18% of the reviewed articles emphasize VR/AR associations applied for visualization purposes. Fukuda et al. (2006) describe VR applied to simulation visualization, where real-time simulation based on virtual reality technology is developed for environmental design evaluation. Portillo, Amen and Flores (2010) present the development of an AR application for Smartphone to reformulate the vision of the society on urban and archaeological heritage in relation with new technologies.

17% of the articles address applications of VR and AR in architecture. Balakrishnan, Kalisperis and Sundar (2006) apply immersive VR associated with psycho-physiological measures in order to capture the affective component of the digital architectural experience. Seichter (2003) applies AR to support a collaborative sketching application.

13% of papers presented a theoretical discussion about VR and AR technologies. In this classification falls Seichter (2005) which analyzes perception and collaborative work using tangible interfaces with AR in a design studio, discussing the concept of usability evaluation with a focus on fundamental theories.

Visualization with VR and AR is mentioned in 10% of the total sample. Wu (2009) examines VR being widely used to present architectural design in space

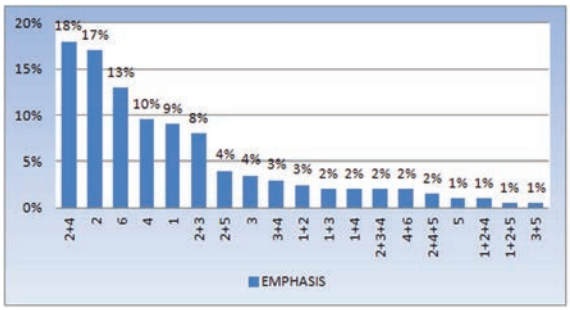

Figure 2. Distribution of publications according to emphasis in: (1) Education, (2) Application, (3) Collaboration, (4) Visualization, (5) Practice, (6) Theoretical discussion.

without the users' knowledge on the subject, facilitating the understanding of the built environment through realistic visualization.

9% of the read articles deal with technology in education. Navarro, Fonseca and Puig (2011) define and evaluate a method for using AR applied in disciplines of graphical representation. It was observed that the use of new technologies promotes student's motivation in the learning process in a practical and intuitive way. However, the accuracy of the result is variable. Nevertheless, faster visualization increases interest in improving errors.

3.3. TECHNOLOGY DEVELOPMENT

The reviewed studies, when look through the lenses of technology development, demonstrate focus on evaluating VR and AR systems, followed by system or tool implementation effort and its demonstration and finally presenting the specification of a wished VR or AR system (Figure 3).

Technology evaluation was described in 26% of the analysed articles. Huang et al. (2001) addressed a discussion about technology assessment by investigating the similarities and variations between computational techniques, principles of interaction and its application in order to understand the process and allow designers to adopt different means of communication during the design phases.

21% of read articles described system or tool implementation effort and its demonstration. Ucelli, Conti and De Amiccis (2005) argue that design environments based on VR should be connected to repositories to facilitate the access and reuse of information. These authors describe the development of a framework for incorporating a VR based design environment and a knowledge management system for multimedia content. The main objective of the research was to propose an

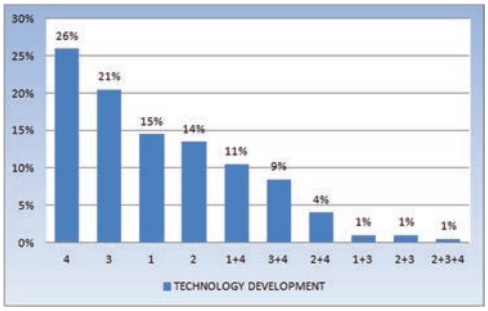

Figure 3. Distribution of publications according to stage of technology development as: (1) Specification, (2) Development, (3) Implementation & Development, (4) Evaluation.

original and innovative approach to assist the design process through the use of new media and technology solution.

System or tool specification was addressed in 15% of the sample read articles. As an example of paper with focus on technology specification Hirschberg et al. (2006) explain the technical aspects of tracking technology with VR/AR and give an overview of possible use in architectural design.

14% of the articles address the development phase to VR/AR. Wang (2007) presents a systematic framework that proposes the concept of mutual increase, i.e., the co-existence of entities of AR and AV (Augmented Virtuality), creating a new integrated and shared space.

4. Featured Authors

Figure 4 presents the top five positions in number of publications featuring 12 main authors in VR and AR in annual conferences of the ACADIA and its sibling organizations over the period from 2000 to 2011. By searching for the institution where these authors were at the time of publication or are now, the related knowledge silos on VR and AR can be drawn to be at: University of Strathclyde (UK), Osaka University (Japan), University Weimar (Germany), Graz University of Technology (Germany), Technische Universitat Muchen (Germany), University of Thessaly (Greece) and University of Sydney (Australia).

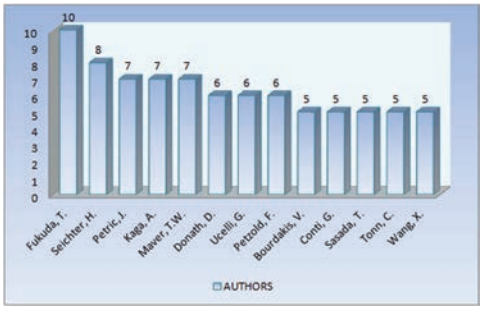

Figure 4. Top ten positions of authors that published in last 11years in ACADIA events.

5. Publication Distribution in Time

Despite the extension of the analytical period (11 years) and the number of articles found addressing VR/AR in this survey, it was observed that the rhythm of VR/AR articles published in annual conferences of the ACADIA and its sibling

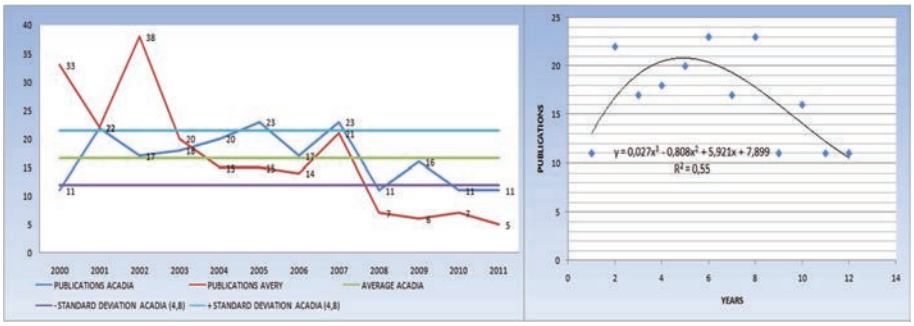

Figure 5. Curves of publications in ACADIA and Avery, average, standard deviation and statistical correlation of published articles in the period of study in ACADIA conferences.

organizations was irregular. It is possible to infer a pattern of decrease or maintenance of publications in the subject. However, caution must be taken in transforming this result in a tendency, for the statistical correlation between articles published in function of time is weak. However, a similar pattern in decrease of publication of articles related to VR/AR was encountered in Avery Index to Architectural Periodicals (Figure 5).

Analyzing the events separately, also with caution, it was observed that publishing patterns differ among conferences. While ACADIA, CAADRIA and ECAADE show decrease of interest in VR and AR, CAAD Futures, SIGRADI and ASCAAD slightly point in the direction of maintenance or increase.

6. Conclusions

Surprisingly, it was observed that the rhythm of VR and AR articles published in annual conferences of the ACADIA and its sibling organizations was irregular over the period of study and that there is a slight pattern of decrease or maintenance of publication. Since central concepts in CAAD change with time (Bhatt and Kishore, 2008), a closer look must be taken in order to understand if the decrease in VR/AR publications denotes a decrease of research interest or a more precise delimitation of the topic.

In terms of research study areas, most articles address transformation in design process with the incorporation of VR and AR. In these studies there is emphasis on tool appliance and its use for visualization followed by theoretical discussion over technology, application in education, application in collaboration and practice. The technology is in most cases evaluated, but also implementation efforts are presented; which indicates the constant need for innovation follow-up.

The survey of activity demonstrates that possible benefits of these technologies, when applied in design process to understand and communicate ideas, are noticeable. However, VR and AR have not been yet fully incorporated in architectural practice, despite its almost half century existence and evolution in other technical areas. Education is an important driving forces promoting technology appropriation in practice.

Acknowledgements

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References

Amin, R. R.: 2007, *Realidade Aumentada aplicada à Arquitetura e Urbanismo*, Universidade Federal do Rio de Janeiro, Rio de Janeiro.

Ahmad Rafi, M. E. and Karboulonis, P.: 2000, The Re-Convergence of Art and Science: A Vehicle for Creativity, *5th Conference on Computer Aided Architectural Design Research in Asia CAADRIA2000*, Singapore, 491–500.

Azuma, R. T.: 1997, A survey of augmented reality, *Presence – Teleoperators and Virtual Environments*, **6**(4), 355–385.

Balakrishnan, B., Kalisperis, L. N. and Sundar, S.: 2006, Capturing Affect in Architectural Visualization – A Case for integrating 3-dimensional visualization and psychophysiology. *24th Conference Education and Research in Computer Aided Design in Europe (eCAADe)*, Volos, 664–669.

Bhatt, A. and Kishore, A.V.V.: 2008, Studying Corpus Changes in CumInCAD, *26th Conference Education and Research in Computer Aided Design in Europe (eCAADe)*, Antwerpen, 855–860.

Bhatt, A. and Martens, B.: 2009, The Topic of CAAD: An Evolutionary Perspective, *13th International Conference on Computer Aided Architectural Design Futures-CAAD-Futures*, Montréal, 626–641.

Burdea, G. C. and Coiffet, P.: 2003, *Virtual Reality Technology* (2nd ed.), John Wiley & Sons, New Jersey.

Chiu, M. L., Lin, C. J., Jeng, T. S. and Lee, C. H.: 2002, Re-Searching the Research Problems In CAAD: Data Mining in i-CAADRIA, *7th International Conference on Computer-Aided Architectural Design Research in Asia – CAADRIA*, Cyberjaya, 31–38.

Fukuda, T., Sakata, K., Yeo, W. and Kaga, A.: 2006, Development and Evaluation of a Close-range View Representation Method of Natural Elements in a Real-time Simulation for Environmental Design – Shadow, Grass, and Water Surface, *24th Conference Education and Research in Computer Aided Design in Europe (eCAADe)*, Volos, 58–65.

Guimarães, C. P.: 2007, Virtual Reality and the Visual Image [Realidade Virtual e Visualidade na Imagen], *11th Iberoamerican Congress of Digital Graphics – SIGRADI*, Mexico D.F., 78–82.

Hirschberg, U., Sayegh, A., Frühwirth, M. and Zedlacher, S.: 2006, 3D Motion Tracking in Architecture – Turning Movement into Form – Emerging Uses of a New Technology, *24th Conference Education and Research in Computer Aided Design in Europe (eCAADe)*, Volos, 114–121.

Höhl, W.: 2009, *Interactive Environments with Open-Source-Software – 3D Walkthroughs and Augmented Reality for Architects with Blender 2.43, DART 3.0 and ARToolKit 2.72*, Springer Wien New York, Vienna.

Huang, Y. H., Liu, Y. T., Lin, C. Y., Chen, Y. T., Chiu, Y. -C., OH, S., Kaga, A. and Sasada, T.: 2001, The comparison of animation, virtual reality, and scenario scripting in the design process, *6th Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA)*, Sydney, 231–239.

Kalisperis, L. N., Otto, G., Muramoto, K., Gundrum, J. S., Masters, R. and Orland, B.: 2002, Virtual Reality/Space Visualization in Design Education: The VR-Desktop Initiative, *20th Connecting the Real and the Virtual – design Education Conference*, Warsaw, 64–71.

Kirner, C., Kirner, T. G., Calonego, N. Jr and Buk, C. V.: 2004, Uso de Realidade Aumentada em Ambientes Virtuais de Visualização de Dados. *7th Symposium on Virtual Reality – SVR 2004*, Sociedade Brasileira de Computação (SBC), São Paulo, 149–160 p.

Maver, T. W.: 1995, CAAD's Seven Deadly Sins, *6th International Conference on Computer Aided Architectural Design Futures-CAAD-Futures*, Singapore, 21–22.

Navarro, I., Fonseca, D. and Puig, J.: 2011, Aplicación docente de Realidad Aumentada en cursos universitarios de representación de proyectos de Arquitectura [Case study of application of augmented reality in university courses for representation of projects of architecture], *15th Iberoamerican Congress of Digital Graphics – SIGRADI*, **15**, Santa Fe, 74–77.

Okeil, A.: 2010, Hybrid Design Environments: Immersive and Non-Immersive Architectural Design, *15th Journal of Information Technology in Construction ITcon*, 202–216.

Portillo, B. J. P., Amen, F. G. and Flores, L.: 2010, R:DAR Regions, Areas, and Directioning in Augmented Reality: un estudio para el móvil Samsung I8000 Omnia II [RA:DAR Regions, Areas, and Directioning in Augmented Reality: a case study for the Samsung mobile phone 18000 Omnia II], *14th Iberoamerican Congress of Digital Graphics – SIGRADI*, Bogotá, 125–128.

Seichter, H.: 2005, Assessing Virtual Tangibility, *11th International Conference on Computer Aided Architectural Design Futures-CAADFutures*, Vienna, 151–169.

Seichter, H.: 2003, Sketchand+ a collaborative Augmented Reality sketching application, *8th International Conference on Computer-Aided Architectural Design Research in Asia – CAADRIA*, Bangkok, 209–222.

Ucelli, G., Conti, G. and De Amicis, R.: 2005, Shape knowledge embedded in a collaborative virtual design environment for architectural design, *23rd Conference Education and Research in Computer Aided Design in Europe (eCAADe)*, Lisbon, 373–381.

Wang, X.: 2007, Mutually Augmented Virtual Environments for Architectural Design and Collaboration, *International Conference on Computer Aided Architectural Design Futures-CAAD-Futures*, Sydney, 17–29.

Wang, X. et al.: 2008, An Empirical Study on Designers' Perceptions of Augmented Reality within an Architectural Firm, *13th Journal of Information Technology in Construction ITcon*, 536–552.

Wu, Y.-L.: 2009, Some Phenomena in the spatial representation of Virtual Reality, *14th International Conference on Computer-Aided Architectural Design Research in Asia – CAADRIA*, Yunlin, 143–152.

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MODEL COMMAND

Spatial comprehension of 3D digital environments

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Abstract. The paper explores innovative methods of navigation for experiencing and spatial comprehension of complex 3D digital environments. Common navigation modes of digital environments are difficult to learn and use within complex multi level digital models and often result in the viewer becoming disoriented or stuck. By drawing on concepts from computer gaming and spatial way finding this research will explore intuitive navigation systems. These systems enable the user to engage and experience the digital space much more profoundly than current CAD and BIM model viewing software. The paper demonstrates these navigation spatial cognition systems through three case studies.

Keywords. Navigation; BIM; spatial comprehension; orientation.

1. Introduction

Digital 3D models are common tools in design and construction processes. Yet, interacting within these models can be frustrating, progressively as the models increase in complexity. Due to the increased use of building information modelling (BIM) during the design phase, the construction and facilities management phases now have access to comprehensive digital models. Resulting in a different type of spatial cognition and investigation required of a complete model compared to the creation and editing of a digital model. There is a comprehensive collection of research around the navigation in virtual environments dating back over 20 years. Yet navigation and disorientation are still significant problems (Kopper et al., 2006; Khan et al., 2008). This research project primarily explores methods of navigation for experiencing complex 3D digital space. With the increased use of BIM comes the importance of accessing location-based information. The scope of this paper focuses on post content-creation to the intellection of complex digital models.

Michael Glueck and Azam Khan (2011) of Autodesk Research argue that "Navigating an environment is intrinsically linked with understanding that environment." Current CAD software predominantly provide methods of navigation to aid in the creation of 3D digital models based around modal tools for example; pan, zoom, orbit, etc. All of these tools provide a disjointed singular method of navigation, making navigation extremely infuriating, confusing and disorientating delaying the understanding of the environment for the user.

In the context of this paper a complex digital model is defined as a three-dimensional model, constructed with CAD or BIM software, of a building that has detailed interior and exterior geometry, is multi-storied, and strong spatial presents at multiple scales. It is difficult to view the entire model from one scale. This is in comparison to an object with little or no interior definition that can be completely viewed by orbiting around the objects centre while at a constant scale.

2. Spatial Cognition

"Navigation is the cognitive process of acquiring knowledge about a space, strategies for moving through space, and changing one's metaknowledge about a space," according to Laura Leventhal (Jul and Furnas, 1997).

A user who is exploring a model (not creating or editing) needs to generate a 'grasp' of location and orientation of the building, what Malpas (2007) refers to as a spatial frame, that is used to create what Tversky (1993) describes as a cognitive collage to develop a spatial mental model. The cognitive collage consists of different factors, hieratical representations, cognitive perspectives, cognitive reference points, alignment to other locations, rotation to frame of reference, and more, can distort spatial comprehension. How can these factors develop navigation and spatial cognition within a complex digital model?

2.1. NAVIGATION

The main navigation tools in CAD software are effective at the navigation of an object (a simple model) compared to complex models (e.g. a digital model of a building). Pan, zoom and orbit enable fast navigation of a simple model, these tools do not translate well for navigation and spatial comprehension of complex digital models. A number of software packages include spatial navigation tools; walk, fly and look that try to address navigating complex models, however these tools are mono-functional. They only work in one role and the user has to change tools from Walking to Looking, interrupting the users flow, creating a fragmented navigation experience. Researchers Glueck and Khan (2011) state "interacting

with these environments can be challenging for users, especially as these environments increase in complexity and scale."

It is easy to become disoriented and lost within a digital building model when only using standard CAD model navigation tools. The model elements are non-solid representations of real-world building components that can be passed through by the viewer, contributing to disorientation and a loss of sense of scale. The paper explores a range of navigation and orientation systems to enable efficient spatial comprehension via more usable humanistic methods of navigation. Commercial computer game engines enable a multi-functional first person (and third person) navigation view that provide a consistently scaled view of a digital space that is navigated by walking or flying. This mode of navigation provides the viewer a smooth and uninterrupted navigation flow that enables a stronger understanding of scale and relationships, spatial cognition within a proposed building than standard mono-functional navigation tools. A number of recent reviewing software packages have included these options of navigation tools, however it is still possible to become stuck in corners–if one attempts to move through solid geometry–and lost.

Construction drawings have developed in relation to the technologies available to architects and restrictions of the media. Within the established protocols of construction drawings, no conventions currently exist for the review and navigation of 3D digital building models. A number of "standard tools" of navigation operate across different software packages, however each tool operates slightly differently in each package resulting in confusion and conflict for the user.

2.2. ORIENTATION

Comprehending ones orientation within a complex digital model increases with difficultly in parallel with model complexity. Users cognitive collage and spatial cogitation is informed by their spatial frame of reference and task. Currently there are not many orientation markers beyond the model geometry in CAD viewing software that aid in providing clues to the users. Recent additions of CAD viewing software have included real world constraints of user collision and gravity, basic light and shadow rendering. These additional orientation aids are still very crude and can still be a hindrance to movement with in a complex digital model. Alongside the constraints has been the addition of 'saved views' that an author can predefine. Although useful for creating fast access to predetermined spatial locations, there is a disconnect for a user new to a model as there is no orientation to or from the saved view, resulting in a gap in their spatial mental model. The following case studies explore possible methods to improve spatial cognition.

3. Case Studies

The case studies have developed sequentially, starting with the Point Model that was an investigation into methods of navigation used with in computer gaming on desktop and tablet computers. After a critical review of existing software and case study one, Pathfinder Model, case study two was developed to help improve spatial cognition during basic model navigation by introducing innovative methods of navigation. A third case study, Space Trace, explored an abstracted spatial condition utilising sensors to control the navigation of the model. Significant methods explored in the case studies include a prolonged transition or spatial transition and artificial intelligence (AI) path finding.

3.1. POINT MODEL

The Point Model addresses modes of navigation that draws from the game Epic Citadel 2010 by Epic Games, Inc., that enables players to tap the screen to move their avatar to the touched location. To enable this to happen with a mouse click, Point Model introduces a glowing yellow pointer in 3D space that, on holding the left mouse button, the user can move it around the visible part of the model (Figure 1 and 2). Then once the user has located the pointer at a desired destination a left mouse button click moves the view to that location. The movement is a

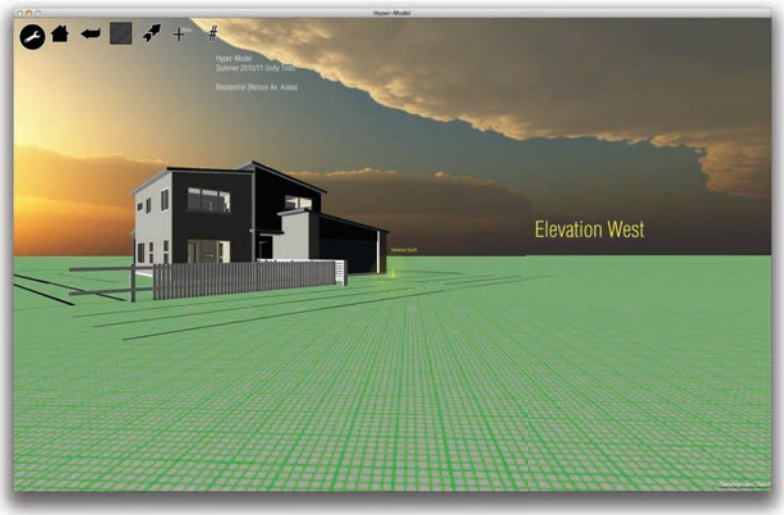

Figure 1. Point Model starting view.

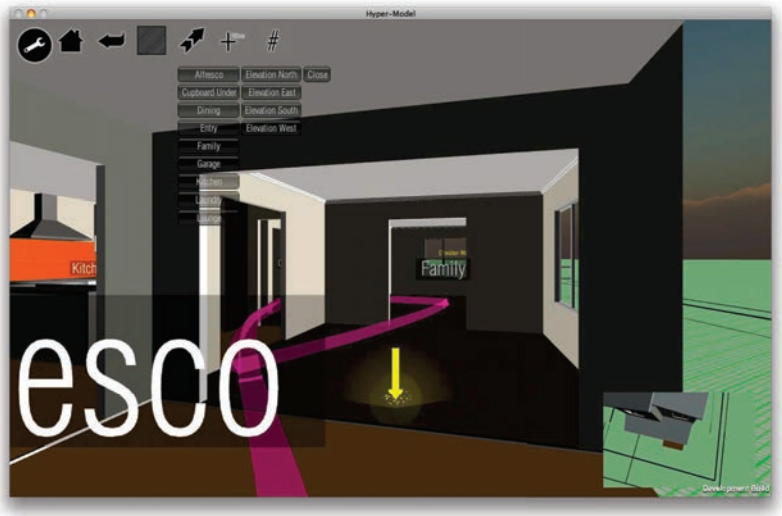

Figure 2. Point Model yellow arrow and magenta trail.

timed transition through digital space that helps to build the spatial cognition of the user. Providing the user with a destination based navigation rather than the use of navigation tools to get to desired location.

With the spatial transition of the view, a magenta coloured trail or breadcrumb is left, providing the user a visual marking of their movement through the model, providing another element that helps to build the users spatial mental model (Figure 2). The trail has a defined life, and dissolves after one minute, so as not to over complicate the digital space. It is a straight-line movement to the pointer, resulting in the possibility of the becoming blocked by solid geometry, requiring another movement.

At any time the user can used the 'WASD' keys – a standard computer gaming navigation control for walking forward (W), backward (S), sideways (A and D) – to walking the user whilst clicking and holding the left mouse button to look around, multi-function navigation mode. Other navigation methods include; a small location plan in the bottom right of the screen, that locates the users in context of the building, a home button that returns the user to a fixed starting point, and Undo Move button that transports the user to back to their last location.

3.2. PATHFINDER MODEL

On reflection of the navigation methods explored in Point Model, all of the methods introduced needed further devolvement. The spatial transition used with in

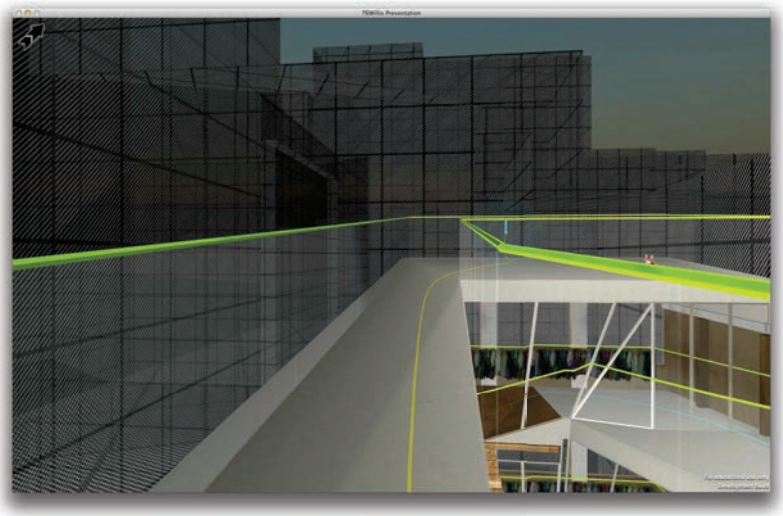

Figure 3. Pathfinder Model, thin yellow indicative trail and cyan trail travelled.

Point Model did not respond to the realities of the building model or aid in improving spatial cognition of the model. In the Pathfinder Model we unitized AI to generate dynamitic spatial transition in real-time that are formed by a 'navigation mesh' that overlays the geometry mesh. Depending on current location and selected destination depends if you are flown or walked. The improved spatial transitions, succour to build spatial; cognition, orientation, location, direction and relationships, by moving the user through a path to the destination a sense of distance and scale is provided. This is not common in CAD and BIM software, and is usually gained from designing and modelling the project, much harder to comprehend from just exploring a finished digital model.

Building on the Pointer Model, a line transparent cyan trail (or breadcrumb) is left representing the path you have travelled, in addition, once you start a spatial transition, a line transparent yellow line is drawn indicating the path you will follow (Figure 3). Both of these aid in building the users spatial comprehension by charting their path suggested and travelled, to stop confusion over time, the trails disappear after 30 seconds. If the user decides to move to another objective, the spatial transition can be stopped in its tracks directed to another destination or the user is free to walk around.

Predefined views have been created to provide standard architectural representations in perspective projection of elevations and plan. The user is then able to scan through the building to gain sectional information (Figure 4). Currently there

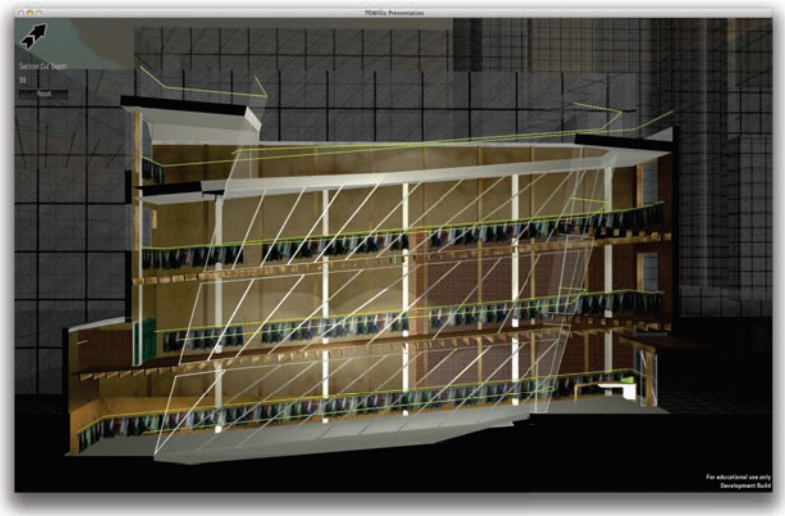

Figure 4. Pathfinder Model section view.

are no predefined section cuts, which is an aspect that the author is investigating further.

Darken and Sibert (1993) have cited spatial audio as a navigation technique in virtual environments, one that is currently not used within CAD and BIM models. This was introduced in Pathfinder Model as a simple sound track for the interior and another for the exterior space. The aural scape provided the user an omnipresent indicator of a binary condition of interiority. The spatial audio gave non-visual navigation assistance, but did not provide any architectural indication of the quality of space beyond a sense of interiority. The author plans to develop further models that explore the audio qualities of space to aid in spatial comprehension.

3.3. SPACE TRACE

Space Trace explored methods of navigation in experiencing an abstracted 3D digital environment compared to the previous two case studies. The project was setup to explore non-standard ways of providing spatial comprehension of a complex unfamiliar digital model.

The context of the project was within a blind peer reviewed exhibition, within the three-day symposium, Wellington LUX, the result of a partnership between Massey University College of Creative Arts, Oslo School of Architecture, Oslo, Norway, Wellington City Art Gallery and Whanganui Art Museum. By drawing

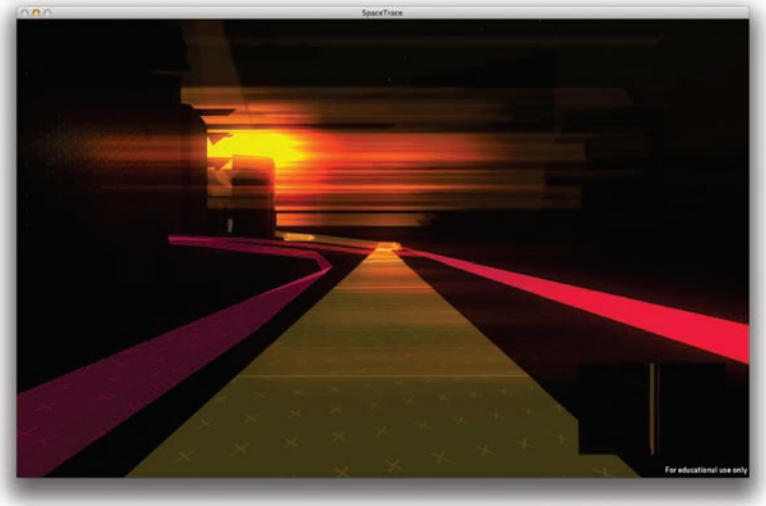

Figure 5. Space Trace, thick yellow indicative trail and magenta trail travelled.

on computer gaming and spatial way-finding, the project demonstrates innovative navigation systems beyond conventional approaches. The work incorporates motion data driven navigation consisting of a static building model and real-time data digitally reconstructed light, geometry and sound. It enabled viewers' to have interactive experience of a spatial context by providing wide trails of yellow light to predefined spaces, creating virtual vibrant violet breadcrumbs to aid navigation and spatial comprehension (Figure 5).

The project enabled exploration of non-standard input to control the sequence of predefined destinations within the model. The installation reacted to the motion of people with in the gallery space moving the viewers through the digital model. The reactive travel through the model provided the viewers a unique understanding of the digital space with out having to control the movement. The project provided an opportunity to move beyond conventional CAD viewing and navigation systems. The findings from Space Trace will be developed into future case studies within architectural projects.

4. Improving Spatial Cognition

Current CAD and BIM software focuses on navigation methods for editing geometry with little consideration to succour spatial comprehension of architectural models. This is due, in part, to limited processing power and attention on 2D

papers based outputs. With the increase of complex BIM models a need to provide effective access to complex digital models has followed. A number of software packages have attempted to address this issue, all struggling to provide empowering navigation and spatial cognition.

Researchers Glueck and Khan (2011) state that intellection and navigation are interconnected, a statement that historically has not been evident in the software. In providing users methods to grasp frames of reference that build a near complete cognitive collage, beyond mono-functional navigation tools, enable enhanced benefit of BIM models for post design tasks. Within current software it is problematic to grasp position, orientation and interiority resulting in users becoming lost and frustrated interacting with a complex digital model.

5. Conclusion

The case studies have emphasised methods of navigation that can assist in spatial comprehension of complex digital models compared to current CAD software. By providing users with spatial transitions that guide them through a building model enabling users an assisted 'gasp' of their location and orientation. Developing this further in case study two, Pathfinder model, with AI navigation to allow dynamitic path finding.

The principle academic contribution of this research paper is that a single method or technique of navigation is an inadequate approach to providing spatial cognition of digital architectural models. Rather the interface between the tools and the conditions within the model needs to be considered in refining, and creating new, navigation methods. That spatial comprehension and navigation are fundamentally connected and is critical in the development of approaches to aid spatial cognition. The pathfinder model illustrates a connected approach that assists the viewer in building a spatial mental model of a digital proposal.

Acknowledgements

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References

Darken, R. P. and Sibert, J. L.: 1993, A toolset for navigation in virtual environments, *Proceedings of the ACM User Interface Software & Technology*, Atlanta, 157–165.

Fitzmaurice, G. et al.: 2008, *Safe 3D navigation: in I3D '08: proceedings of the 2008 symposium on Interactive 3D graphics and games*, Redwood Shores, CA, 7–15.

Glueck, M. and Khan, A.: 2011, Considering multiscale scenes to elucidate problems encumbering three-dimensional intellection and navigation, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, **25**(4), 393–407.

Jul, S. and Furnas, G. W.: 1997, Navigation in electronic worlds: a CHI 97 workshop, *SIGCHI Bulletin*, **29**(4).

Khan, A., Mordatch, I., Fitzmaurice, G., Matejka, J. and Kurtenbach, G.: 2008, ViewCube: a 3D orientation indicator and controller, *I3D '08: Proceedings of the 2008 symposium on Interactive 3D graphics and games*, ACM, New York, 17–25.

Kopper, R., Ni, T., Bowman, D. A. and Pinho M.: 2006, Design and evaluation of navigation techniques for multiscale virtual environments, *VR '06 Proceedings of the IEEE conference on Virtual Reality*, ACM, New York, 175–182.

Malpas, J.: 2007, *Place and experience: a philosophical topography*, 1st ed., Cambridge University, Cambridge, UK.

Tversky, B.: 1993, Cognitive maps, cognitive collages, and spatial mental models, *in* A. U. Frank and I. Campari (eds.), *Spatial information theory a theoretical basis for GIS*, Springer, 14–24.

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COMPUTER VISION AND AUGMENTED REALITY TECHNOLOGIES IN EXPERIMENTAL ARCHITECTURAL DESIGN EDUCATION AT THE AA

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Abstract. This paper aims to investigate the potential of both open source software and new media (esp. computer vision and augmented reality) as tools for architectural design and education. The examples illustrated in the paper would be drawn mainly from students' projects done as part of their AA Media Studies Course submission at the AA School of Architecture (AA) during the academic years from 2011/2012 to 2012/2013. The paper outlines the main approaches, which students have chosen to implement, both directly and indirectly, these new media and tools into their studio work at the AA. Section 1 briefly introduces a range of currently available open source computational design toolkits that are deemed useful for quick implementation of computer vision and augmented reality technologies. The related programming languages, softwares and hardwares would also be introduced and described accordingly. Sections 2 and 3 are accompanied with a visual catalogue of students' projects to better illustrate the diversity in the understanding and implementation of computer vision and augmented reality technologies in architectural design. Section 4 serves to conclude the paper by first discussing briefly the feedback from students at the end of the course before clarifying the context of the research and thus its relation to recent work done by others using similar technologies.

Keywords. Computer vision; augmented reality; generative design; interaction design.

1. Introduction

The use of Computer Vision and Augmented Reality Technology as a tool for spatial design exploration has become more accessible to both designers and the general public in recent years. In addition to hardware affordability, the various widely available open source software tools and a rapidly growing community of complementary online forums or downloadable tutorials, where technical know-how are being shared freely, have given rise to a new mode of architectural design exploration both in cutting-edge academia and design practices.

The possibility to extract accurate spatial/depth data of real physical environments/objects and further embed their augmented forms virtually suggest great potential of such tools to be included in the architect's standard digital toolbox of CAD/CAM technologies. However, the necessary programming skill-sets needed to best utilize these newly acquired tools proved rather challenging to the typical architectural students, despite the progressive inclusion of scripting courses in recent architectural design syllabus.

In order to facilitate a more conducive learning experience, the choice of software to be taught in the classroom is critical to the success of this endeavor in introducing new hardware and software knowledge simultaneously. At present, among the various creative coding open source software environments, there are generally 2 types of environment: 1) Visual/Graphic Programming and 2) Text-based Programming. The former is more visual whereby students use 'patches' to make more complex 'definitions' to perform the computation. These include Max/MSP, Quartz Composer, Rhino Grasshopper, Scratch…etc., each is well-supported with their corresponding Kinect wrapper/libraries. On the other hand, the latter includes Processing, Openframeworks, Cinder…etc. These are typically based on higher-level programming languages (e.g. Java, C++, Python…etc) with or without their own IDE. The decision to eventually use Processing in the course is due to various reasons from a teaching and learning perspective. It is the intent to provide a greater range of possible entry levels for students with different or no programming experiences and thus allowing them to more easily migrate to other programming languages in the future. At the same time, the existence of a thriving online community of Processing developers and resources also suggest the ongoing popularity and usefulness of the software concerned. The excellent API/documentation and thus the widespread usage of Processing among other design disciplines is another main factor that is considered, other than the relatively gentler learning curve of the programming language. Although a C++ based programming tool would be deemed much faster in real-time computation, the difficulty of the language is the main disadvantage as an introductory programming course for architectural students.

2. Kinect

2.1. TRACKING SKELETON DATA: SPATIAL ENVELOPE AS STRUCTURES & FASHION WEAR

The Microsoft Kinect Sensor has the capability in extracting and tracking multiple users' skeleton data in real-time. The joints position and their corresponding joint orientation allows one to compute spatial envelopes which reconfigures itself based on the spatial relationships among the tracked body joints. The available skeleton data includes feet, knees, hips, torso, shoulders, elbows, hands and heads.

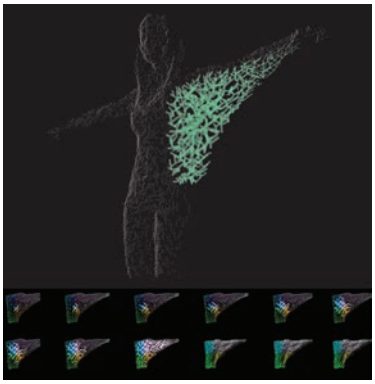

Figure 1. Branching structural networks constrained by a virtual search space defined by the specified body joints.

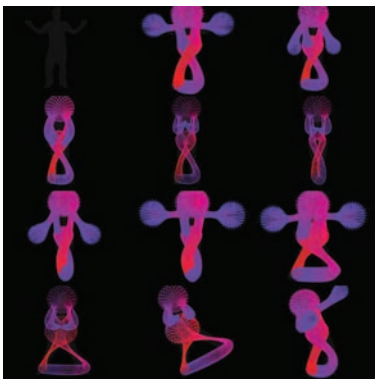

Figure 2. Responsive interweaving fashion wear.

In particular, Project 1 (Figure 1) has used this capability of the technology to great effects. The students set out to generate a series of prosthetic armatures using the joints' spatial relationships. A volumetric mesh 'container' is generated in real-time, which then becomes the 'search space' for the deployment of a branching algorithm. The branching geometric construct is an attempt to create a generative network of structural support that would eventually be 3d-printed with ABS or fibre-carbon material. Variations in density, profile, directionality and thickness of the branches are being generated based on the volume enclosed by the designated joints. Since the spatial dimension of each joints' position would varies according to different users' body frame and body language, this tracking prototype suggests the potential to generate customised prosthetic profiles for every individual. In addition, this prototype is programmed to output the geometries as standard CAD/CAM file format, thus facilitating a smooth workflow incorporating digital fabrication processes. Although the output and subject of this project may seemed more akin to a product design exercise, however, the skill sets and design approach adopted here is applicable and scalable in an architectural context.

In the case of Project 2 (Figure 2), the student constructed the entire virtual envelop of the body to create a prototype for an interactive fashion wear. A variety of cross-sectional profiles are aligned both in position and orientation to the corresponding body joints, where a continuous set of splines would then thread through them, forming a complex interweaved envelope. Each individual cross-section is a polygon that varies its scale and number of sides based on the proximity of its opposite joints (i.e. the distance between the left limbs and right limbs), thus changing the density of the overall network. Although the constant reconfiguration of the proposed fashion wear

is visualized graphically, the concept can be further implemented with elastic fabric, LEDs, micro-controllers and sensors (e.g. LilyPad Arduino and flex sensors, etc.).

2.2. TRACKING USERS' 2D PIXELS/3D POINT CLOUD: DANCE PERFORMANCE AS AN INTERACTIVE 2D SILHOUETTE PROJECTION AND A DYNAMIC 3D TRACE

In both Project 3 and Project 4, professional dancers become the co-creators, alongside the students, of the generated virtual space/form. Both attempt to visualize the energy of each dance move and further enhance the experience.

In Project 3 (Figure 3), the intention is to enhance the dance performance by projecting visual effects onto the dancer's body in real-time. This is achieved by embedding interactive particle-systems within the extracted 2D silhouette of the dancer. The movement of the particles would response according to the outline of the projected silhouette, thus any contrasting and abrupt dance move would immediately intensify the collision behaviour of the particles, especially those along the boundary of the silhouette. The Kinect is used here to first extract the dancer's 2D pixels and translating it into a Gaussian blur image before undergoing a blob detection algorithm. The algorithm aids in the extraction of the body's silhouette as an enclosing polyline. This closed polyline would act as the boundary constraint where particles with varying collision behaviour interact. Since the computation and visualization occur in real-time, the performing dancer responses directly to the visuals and intuitively alter his/her subsequent dance move. The project proposed an improvised space of encounter.

In Project 4 (Figure 4), another student attempts to 'freeze' the dancer's move in 3D space. The Kinect sensor is able to extract the depth map of the dancer at any point in time and project these as a 3D point cloud. In this way, the dance could be viewed in a 3D virtual space whereby one could navigate the view using the cursor

Figure 3. Dancer improvising based projected particle system on his body silhouette.

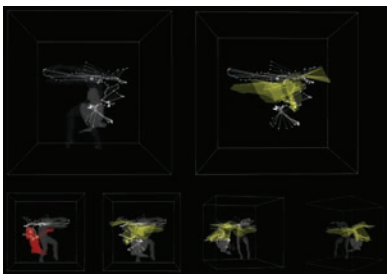

Figure 4. 3D Point cloud traces of a dancer.

to pan, orbit and zoom. Similar to the Project 3, the dancer is able to response to his/her previously 'frozen' point cloud and improvise based on the newly generated spatial entity. In fact, the code is programmed in such a way that whenever there is a prolonged pose during the performance, a set of the dancer's point cloud would be deposited on the 3D scene. In addition, certain designated joints would continuously trace their movement and generating 3D meshes. This project illustrates the use of the Kinect as a potential tool to record and evaluate body movement in 3D space.

2.3. GESTURAL RECOGNITION: PHYSICAL HANDS AS VIRTUAL CRAFTSMAN'S HANDS

The Kinect sensor is able to recognize a list of human gestures, such as waving, raising and swiping the hands. Unlike the earlier projects, which require an initial full body pose calibration in order to extract any skeleton data, here the sensor only requires gesture detection without even a full view of the body. In Project 5, the students begin with a concept to reflect the nature of the Kinect's scanned data. The scanning technique used by the Kinect is a variation of the standard Structured-Light 3D scanning system. Instead of projecting stripes of visible lights and measuring the deformation of the reflected light, the Kinect projects patterns of infrared light. However, regardless whichever variation of the system, the data collected is always based on a specific view rather than a full 360 degrees scan. The students understood this technical limitation and decide to scan and create objects based on the simple principle of axial and planar symmetry. For instance, a table lamp has an axial symmetry while a human head has a planar symmetry. The final proposal combines the Kinect's capability in gesture recognition and the concept of symmetry to create a new design interface. With this interface, any user could use their hands to virtually sculpt a series of symmetrical scanned objects. For instance, the Digital Potter's wheel interface (Figure 5) allows users to sculpt the objects in way resembling a pot-

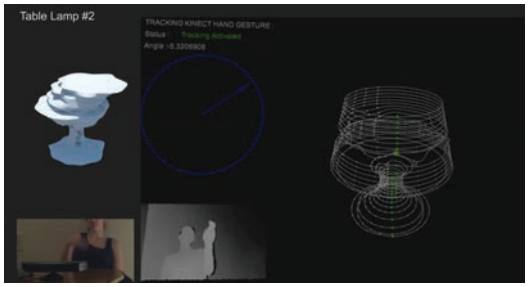

Figure 5. Digital Potter's wheel interface detecting hand gesture to sculpt scanned objects rotating around its line of axial symmetry.

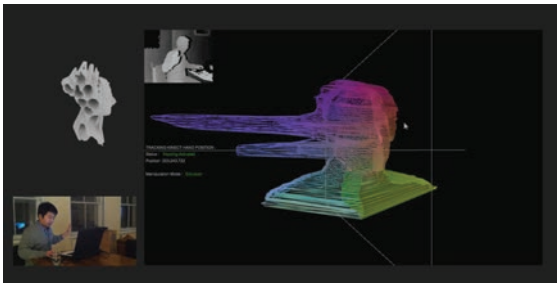

Figure 6. Digital Mirroring interface detecting hand gesture to sculpt scanned head with planar symmetry.

ter 'spinning clay'. In the Digital Mirroring interface (Figure 6), users only sculpt one side of the object and the other side would generate an inverse form along the plane of symmetry. Once the user is satisfied with the newly sculpted versions, the files could be directly sent for 3D printing or CNC milling.

3. Augmented Reality (AR)

3.1. AR MAKERS AS AUDIO MARKERS

AR markers not only allows one to map virtual 3D objects onto a physical plane, it could also be used to trigger audio samples. In Project 6 (Figure 7), the student uses both 'Processing' and 'Ableton Live' (an audio sequencer) to reinterpret an architectural representation of a plan. By envisioning the plan of Chungking Mansions' ground floor in Hong Kong as a drum machine, each of its hallways becomes a button that triggers the repetitive sound specific to the portion of the building. One could

Figure 7. Series of AR Markers act as an audio sequencer to produce different sound scenarios.

then start to play and overlap different sound scenarios or even to begin a new path through the building's hallway by separately triggering each of the hallways. The traditional 'mute' architectural plan is here embedded with the dimension of sound.

3.2. AR MARKERS AS SOCIAL MARKERS

Project 7 explores how might augmented reality be used as a tool for measuring the interaction intensity of a group of people in real-time. Each student in the class is assigned with an AR Marker and a webcam is used to track their proximity among themselves (Figure 8). The greater the interaction, the more connections are visualized. It is a simple attempt to use AR technology as a tool to understand spatial organization based on the actual interaction of people within the space observed.

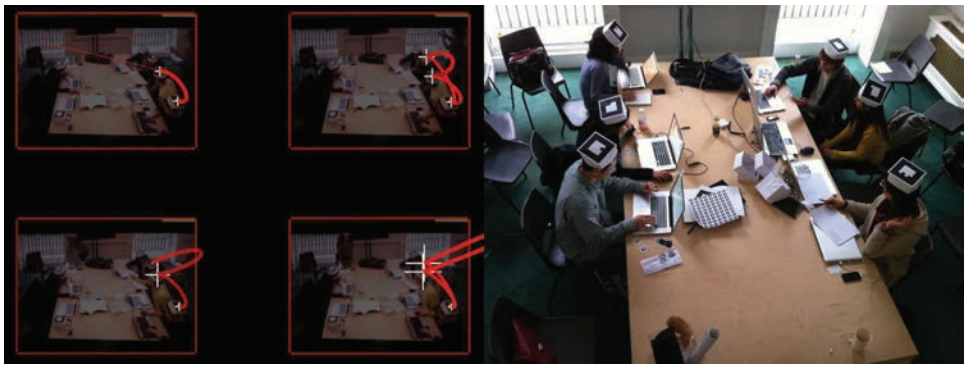

Figure 8. Networks of lines mapping different intensity of students' interaction in class.

3.3. AR MARKERS AS SPATIAL MARKERS

Project 8 (Figure 9) uses AR markers as physical and tangible controllers to gain dynamic control of the overall spatial organisation. By tracking the various AR markers with the webcam and designating them as input points and attractors, the student has proposed an alternative way of architectural modelling.

4. Discussion

4.1. STUDENTS' FEEDBACK

The students' feedback of the course at the end of each term suggests a number of pedagogical issues for considerations. On the positive aspects, students find

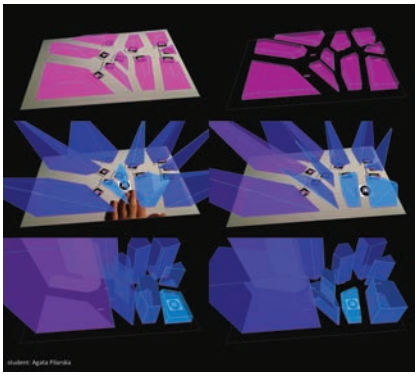

Figure 9. AR markers as controllers for parametric spatial design processes.

learning scripting in an alternative context (i.e. beyond a typical CAD–based implementation context) very liberating and creative, while still allowing them the opportunity to learn the fundamental principles of programming and their actual application in a hands-on manner. The use of open-source software also encouraged students to appreciate the current collaborative/making/hacking phenomenon in our contemporary culture. On the negative side, due to the nature of the course structure (i.e. 3 hours per week with 8 sessions in total), students find learning both the scripting language and the new technologies challenging when asked to appropriate them with their current design studio work. One of the attempts being later implemented to reduce these difficulties among students is to allow them to work as teams of maximum 2–3 people who share similar approaches and techniques, though slightly differing subject matters. In this way, the learning curve of the more technical aspect of their project is greatly reduced while encouraging more brainstorming among them within the teams. Students also find that they could afford more time for the actual design of their proposed projects.

4.2. RESEARCH/TEACHING CONTEXT & RELATED WORK

The Xbox Kinect sensor and Augmented Reality technologies have been increasingly utilized as tools in recent years by researchers to explore a range of highly specific research agenda. Most notably is the Xbox Kinect sensor being used for gestural tracking and 3D scanning. For instance, Fox and Polancic (2012) utilized the Kinect sensor to more accurately tracked the gestures of users as part of their research in developing a gesture-based catalogue of remote controlling dynamic architectural spaces. Here, the technology played the role of evaluating their initially formulated gesture vocabulary. At a more generic level in the use of the

Kinect's gesture tracking capability, Pak et al (2011) used the Kinect mainly as a low-cost and portable touchless interface in forming part of their textile-based portable immersive environment proposal. Roupé et al (2012) presented a similar use of the Kinect but focuses on the body as an interface for virtual reality navigations. All the three references, directly or indirectly suggest that the gesture-based interactions is a more natural interface for spatial manipulation, communication and reasoning. At the other end of the spectrum, Prousalidou (2012) discussed the use of the Kinect as primarily a 3D scanner to extract material data directly from physical model in order to better inform the digital model simulating the design of fabric formwork panels. In this case, the Kinect helps to provide a higher resolution of 3D data in the research.

Each of the references cited above has a clear outline of its research's problems, objectives and methodologies from the outset of its investigation. Typically, the Kinect is a means for them to further validate their hypotheses during the research's real-world testing and evaluation stage. In contrast, the projects illustrated in this paper here attempts to problematize the use of Kinect/Augmented Reality in relation to architectural design as an applied research via the structure of a complementary teaching module, instead of a full-fledged research project spanning a few years within the laboratory. In other words, the process is almost the inverse here. This paper is a direct outcome of the various experiments done within the context of a term long media studies module originally designed to first and foremost to both introduce students to scripting as an important design skill set and to complement the concurrent core studio work of the students from both the AA's undergraduate and graduate schools. Thus, on the outset, each student would already have his/her own research topic and agenda shaped by their respective core studios, each taking on differing trajectories. The course tutor (i.e. author of this paper) would then guide the students, both conceptually and technically, in appropriating the technology (i.e. Xbox Kinect or Augmented Reality) into their intended research specifics, creating a dynamic feedback loop with their core studio work. In this way, the tutor aims to ensure a diversity of approaches being proposed in the exploration of the technology as an applied generic architectural design tool within the limited span of the term-long curriculum. However, some students have chosen to use the course as an independent study, while others did manage to integrate the work with their core studio work in varying degrees of success. The common objectives shared by the projects illustrated in this paper is the experimental appropriation of the selected new media, as well as, the minimal level of scripting competency to be achieved by the students at the end of the term.

This research conducted both in an open framework and in an applied design manner thus insists that it is the task of the architect or designer to make sense of

these new technologies within their design workflow as a means to enrich their design activities and to push the discipline in unexpected directions.

References

Fox, M. and Polancic, A.: 2012, Conventions of Control: A Catalog of Gestures for Remotely Interacting With Dynamic Architectural Space, *ACADIA 12: Synthetic Digital Ecologies*, San Francisco, 429–438.

Pak, B., Vrouwe, I. and Verbeke, J.: 2011, Design and Development of Low-cost Portable Immersive Spaces, *ACADIA 11: Integration through Computation*, Banff (Alberta), 260–267

Prousalidou, E.: 2012, A Digital Model for Fabric Formwork Panels: Using Physical Data to Train the Digital Model, *in* H. Achten, J. Pavlicek, J. Hulin, D. Matejdan (eds.), *Digital Physicality - Proceedings of the 30th eCAADe Conference - Volume 2*, Prague, 159–167.

Roupé, M., Johansson, M., Viklund Tallgren, M. and Gustaffson. M.: 2012, Using the human body as an interactive interface for navigation in VR models, *Proceedings of the 17th International Conference on Computer Aided Architectural Design Research in Asia*, Chennai, 79–88.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 437–446. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

JUDGMENT AND DECISION-MAKING ASPECTS ON THE USE OF VIRTUAL REALITY IN VOLUME STUDIES

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Abstract. The most common reason for using Virtual Reality (VR) as a communication medium in urban planning and building design is to provide decision makers with access to a shared virtual space, which can facilitate communication and collaboration in order to make better decisions. However, there is a risk that judgmental biases arise within the virtual space. The displaying of the VR-models and its content could be one way of changing the settings for the visual access to the virtual space and could thus influence the outcome of the decision making process. For that reason it is important to have knowledge of how different settings in and around the VR-medium influence the experience of the shared visual space that the VR-medium strives to achieve. In this case the decision-making process, perceptions of space, and the cognition process of decoding of information in the visual space are important. This paper investigates how reference points influence judgments of a volume study of a building and furthermore what visual cues that are used for spatial reasoning about volumes. The results show that the initial visual information has a profound impact on the decision, even when this information lacks in validity.

Keywords. Virtual Reality; spatial perception; judgment; volume study; urban planning.

1. Introduction

The use of Virtual Reality (VR) has been seen by many as having potential for increasing the effectiveness and improving communication in the decision making process in urban planning and building design (Kjems, 2005; Westerdahl et al., 2006). The most common reason for using Virtual Reality (VR) as a visualization and communication medium in urban planning and building design is to VR can give decision makers access to a shared virtual space, which can facilitate communication and collaboration in order to make better decisions. VR can facilitate processes so that participants can better understand, identify and analyse problems collectively in order to enhance decision-making and improve the future urban environment. However,

this virtual space could result in a decision-making process that is not bias free. The displaying of the VR-models and their content could be one way of changing the settings for the visual access to the virtual space and therefore the outcome of the decision and thus the future physical space in the real world. For that reason, knowledge of how different settings in and around the VR-medium influence the experience of the shared visual space is important. Previous studies (Kjems, 2005; Westerdahl et al., 2006) have investigated usability issues related to the VR-medium. One conclusion has been that VR inspires to a more dynamic decision making process where different actors can communicate and discuss alternatives (Kjems, 2005). Moreover, visualization can provide actors with a greater sense of certainty of that they are not making poor decisions. However, to our knowledge no studies have investigated the impact the VR-medium can have on the judgment and decision-making process. Furthermore, there are also a number of actors in the planning process that have their own agendas (Ambrose, 1994). If the stakeholders involved in the design of the VR-model have agendas, that are more or less hidden agendas and an interest in a specific outcome of the decision-making process. The VR-medium can be used as a tool to influence the decision-makers towards making decisions in line with these agendas. Moreover, spatial-perception also relies on viewers/stakeholders earlier experience and background (Biederman, 1990; Kosslyn, 1999). It is therefore important to have knowledge about how different viewers decode or recognize the different visual cues in the VR-model and how they use these during spatial reasoning.

The objective of this paper is therefore to investigate which visual cues that are used by the viewer for conducting spatial reasoning about the visual virtual space in the context of a urban planning and how they influence decision making, with a focus on reference point and anchoring effects (e.g. Kahneman, 2002).

- What visual information is used during spatial-reasoning of the volumes?
- How do visual reference points and anchoring points influence how the visual environment is experienced?
- To what extent can reference points in the VR-medium, manipulate the outcome of the decisions in the context of urban planning and building design?

In order to investigate these questions we choose to use material from real urban planning studies. In the next sections related theories concerning decision-making and cognition will be reviewed.

1.1. THEORY FRAMEWORK ON DECISION-MAKING IN URBAN PLANNING AND BUILDING DESIGN

When decision-making takes place in urban planning and building design, it is a very complex, socially structured process, involving both the decisions of individuals and

of groups that are influenced by e.g. social, economic, historical, environmental, physical and spatial factors (Maarttola and Saariluoma, 2002). A seminal contribution to the understanding of decision-making is the concept of bounded rationality (Simon, 1957; Gigerenzer and Selten, 2002) that recognizes the limitations of humans when analysing and evaluating decision alternatives. These limitations can be cognitive and information processing related but it is also affected by limitations such as whether it is time-consuming, whether it requires stable and complete knowledge of all the alternatives, preferences, goals and consequences. The decision maker strives to achieve an optimal decision but given the limitations mentioned above will have to settle for a decision that will frequently deviate from the optimal. The most common issue in urban planning and building design is that the information is not presented in a way so that people can understand it (Hall, 1996; Maarttola and Saariluoma, 2002). It is in this context that the VR-medium can be used as a tool in order to facilitate communication and understanding of the planned new environment. This could be achieved if the visualization is less abstract and that people do not have to spend all their cognitive resources on encoding the visual information from the presentation. VR and motion in the model are necessary for a comprehensive perception of depth cues and, in consequence, for ability to perceive the virtual urban environment. In contrast, perspective static images only communicate "part of the picture" and objects might be blocked or the particular perspective might distort the size and position of certain objects. Therefore, the sense of space requires the ability to navigate interactively through the model (Buziek, 2000; Lange, 2005). Studies have shown that spatial perception of VR-models is different from how reality is perceived (Kenyon et al., 2008). In fact there are many features that are processed during spatial reasoning of the 3D space. Nikolic (2007) argued that for VR-based depth perception, there is a combination of unknowns and uncertainties both real-based and virtual-based ones. One of the main reasons is that viewers' experience a difference between the real environment where the experiment is performed and the virtual one suggested by displayed images. This could be because of low rendering fidelity or photorealism (Sigurdarson et al., 2012) and visual cues and landmarks (Loomis et al., 1999; Riecke et al., 2002; Foo et al., 2005). The display system and their Field of View is also an important factor (Nikolic, 2007). All these factors are dependent on how the VR-medium is set up and the content in the VR-model. The visual cognitive process contain object recognition process that tries to sort the information into patterns, which are then combined and associated with objects that the user has experienced earlier in life (Biederman, 1990; Kosslyn, 1999; Nikolic, 2007). These associated objects are then used in the spatial reasoning process of the 3D space. During this reasoning process the mind tries to create an understanding of the visual space within two parallel systems, i.e. a self-centred *egocentric* reference frame and an environment-centred *allocentric* reference frame (Plank et al., 2010). Both systems

interact during this processing and retrieval of spatial knowledge (Plank et al., 2010). In the egocentric reference frame the viewer compares him/herself with the objects in 3D space and in the allocentric reference frame the viewer compare relations between object-object or environment-object.

Kahneman and Tversky (Kahneman, 2002) have investigated how changing reference points influence the outcome of a decision. All judgments made are made relative to something, whether making judgments of wealth or making perceptual judgments. The underlying processes, being in essence of basic perceptual kind. For instance, how you perceive colour is not only dependent on the current stimulation but to a very large extent dependent on previous perception. The same objective colour can thus be experienced very differently depending on what colour that you were exposed to before. The same holds for practically all-visual perception including the perception of width, height and volume. Kahneman and Tversky have also introduced the important concept of heuristics and biases. Humans have been shown to employ simplifying heuristics in order to make judgments. Kahneman and Tversky observed that the reliance on the heuristics could give rise to systematic errors of judgment, so-called biases. One of the heuristics that was identified is the Anchoring and adjustment heuristic (Kahneman, 2002). The anchoring effect is the common human tendency of making judgments starting out with an initial value or a starting point, (the anchor), and adjusting from this starting point when additional information is made available. The problem is that people frequently adjust insufficiently (Kahneman, 2002). This insufficient adjustment means that the initial anchor (information), regardless of its validity, will have a strong influence on the final judgment.

2. Method

2.1. PARTICIPANTS

The participants consisted of architecture (n = 18), civil engineering students (n = 36) and researchers (n = 6) at Chalmers University of Technology, Sweden. The respondent groups were selected primarily because of their knowledge of and work with urban planning and building design, which is the focus of this study. Thirty-six of the respondents were male and 24 were female. The respondents' ages ranged from 20 to 61 years, with an average age of 26 years (SD = 6.0).

2.2. PROCEDURE

Participants were introduced to the Xbox Kinect interface, which was used to navigate in the Virtual Environments freely using their body (Roupé et al., 2012).

The study was divided into three sub-experiments and in each experiment the participant had approximately 3-8 minutes to explore the different VR-models before answering a questionnaire when in predetermined view points, see Figure 1. The task was to judge the volume of a new building, which is a similar task that is often presented to the city planners and decision makers in the urban planning process. This experiment is actually taken from a real volume study that was conducted in 2008 by the city authority of Gothenburg, Sweden. In the real volume study, the City planners and the local politicians were presented with four different volumes that they had to judge and then decide on which of volume alternatives that the architect would be asked to continue to design. However, in these experiments we have chosen to use 1a and 1b from the real study together with the volume 3 that is currently being built (Figure 1). We also created two new smaller volumes that would represent a smaller alternative to the volume.

During the trials the respondent, with the help of an experiment leader, filled out a web-questionnaire. The experiment leader read the questions to the participants

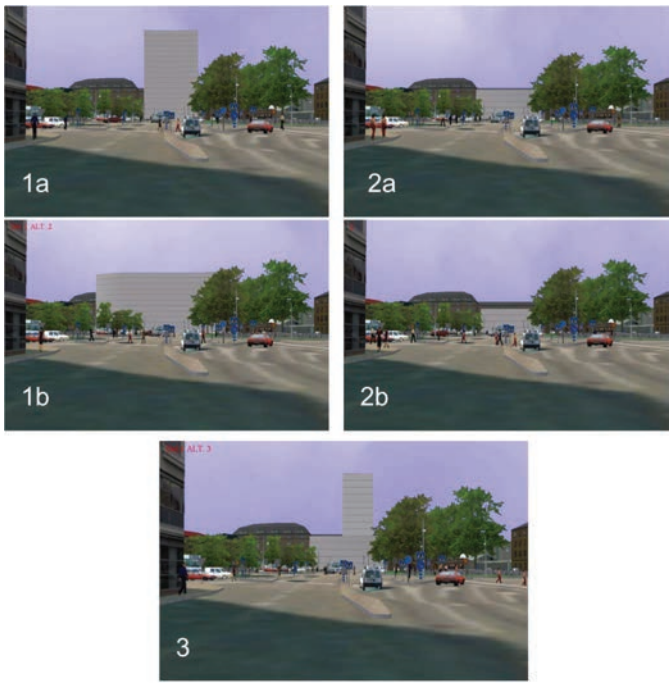

Figure 1. The participants were sub-divided into three groups and had to conduct a volume study of a new building. The first group saw building volume 1a, 1b and 3, the second group saw building volume 2a, 2b and 3, and the third group only saw building volume 3.

and explained the questions in more detail if the respondent did not understand the question. The discussion, answers and explanations on the questions were recorded in order to gain more insight into the user experience. Participants were instructed to think out load during the experiment in order to gain an understanding of how they reasoned when answering the questions. Participates also had the opportunity to see the scales and questions on the left to the displayed VR-model were the projected questions were shown. The questions in the questionnaire were related to: user-experience of the navigation; spatial-perception and architectural experience of 3D-models; and finally decision-making in the virtual environments. The questionnaire included in total 54 variables and questions. The study was conducted with a celling mounted projector with a screen size of 1,65x1,25 m with a Field-of-View of 40,25 degrees.

In this study we wanted to investigate if there are any visual framing effects by presenting the volume study in this manner. The task for the respondents was to judge the volume of the building that is being built, see Figure 1 (alternative 3). Judgments were made regarding the size and form. The first group saw building volume 1a, 1b and 3 (Figure 1) where 1a and 1b were large volumes and the second group saw building volume 2a, 2b and 3 which were small volumes, and the third group saw only building volume 3. All of the sub-groups explored and judged their presented volume alternatives. However, it was only the third the alternative that was considered in the questionnaire in this study. The participants then had to respond on questions related to size, form etc. (Table 1).

3. Results

Table 1 displays the means and standard deviations (SD) for how the respondents perceived and judged the volume of the building (sub-divided groups, see Figure 1 and above). As can bee seen in Table 1, the respondents seemed to use the volumes that were presented before they made their assessment as a reference point for their judgment of the building volume. This effect was most pronounced for item 1.1 “How do you perceive the volume of the house volume?” Alt1 vs. Alt2 (t = (–4.69 (38) $p < .01$) and Alt1 vs. Alt3 (t = (–3.69 (38) $p < .01$). Although the pattern was in the predicted direction, there were no significant differences for the other items. A notable observation was that they did not think that the other alternative influenced their judgment of the house volume when it clearly did (see item 1.3).

In Table 2, the result from the question related to what visual information that was used to do spatial-reasoning about the new building volume.

During the estimation of height in floors, 17 (28.3%) of the respondents mentioned that they comparing the lower part of the building with the total building

Table 1. Means SD for non-qualitative question (n = 60).

Item/Question (Seven step scale) Number of responses for each sub-group (n = 20)	**Case 1, Alt 1. Mean (SD)**	**Case 2, Alt 2. Mean (SD)**	**Case 3, Alt 3. Mean (SD)**
1.1 How do you perceive the volume of the house volume? *(Small = 1, Large = 7)*	4.051 (1.05)	5.452 (0.83)	5.102 (0.72)
1.2 When you made the assessment on the size, to what extent did you compare it to the existing buildings? *(Very low extent = 1, Very high extent = 7)*	5.55 (1.43)	5.20 (1.73)	5.75 (1.41)
1.3 When you made the assessment on the size, to what extent did you compare it to the previous volumes you have seen? *(Very low extent = 1, Very high extent = 7)*	3.60 (2.06)	3.10 (1.71)	–
1.4 How tall do you estimate that the house is in meters?	42.25 (13.52)	40.79* (10.70)	41.21** (11.18)
1.5 How many floors do you estimate that the house has?	12.75 (2.61)	11.85 (2.11)	13.60 (1.85)
1.6 How hard is it to estimate the volume of the house? *(Easy = 1, Hard = 7)*	3.60 (1.31)	4.00 (1.69)	3.20 (1.61)
1.7 Does the house volume fit with its surroundings and nearby buildings? *(Very low extent = 1, Very high extent = 7)*	4.35 (1.66)	3.60 (1.70)	3.90 (1.33)
2.1 How appealing is the form of the house volume? *(Little = 1, Much = 7)*	3.80 (1.44)	3.80 (1.51)	3.60 (1.50)
2.2 How stimulating is the form of the house volume? *(Little = 1, Much = 7)*	3.85 (1.35)	3.20 (1.24)	3.15 (1.39)
2.3 How attractive is the form of the house volume? *(Little = 1, Much = 7)*	3.95 (1.39)	3.55 (1.40)	3.15 (1.35)
2.4 How original is the form of the house volume? *(Little = 1, Much = 7)*	3.75 (1.58)	3.50 (1.43)	3.25 (1.41)

Note: Subscripts that differ indicate significant differences at p = .01.
*N = 19 (one outlier, 12 m was removed). **N = 17 (two outliers, 100m and 150m were removed).

height. During this tasks the participants' hade to think-out loud and explain how they decoded the volume. The verbal protocols showed that the judging of the volume was done in different reference plans e.g. the building façade plane. Furthermore, the estimates of the volume was done in both e.g. egocentric and allocentric frame of reference. In this reasoning process they used known objects (e.g. size of the objects and buildings) in the scene. As can be seen in Table 2, the

Table 2. Reported comments about: What kind of visual information did you use to estimate the building's height in meters and in floors?

Category **Number of responses (n = 59)**	**Visual information for estimate height in meters**	**Visual information for estimate height in floors**
Surrounding building	47 (78.3%)	35 (58.3%)
Lines	35 (58.3%)	48 (80.0%)
Reference objects/details	20 (33.3%)	7 (11.7%)
Earlier experiences of places/buildings	5 (8.3%)	4 (6.7%)

surrounding existing buildings and their façades was an important feature that was used as a reference during the spatial reasoning. The added objects where also important. The participants that mentioned object, mentioned cars 15 times, people/avatars 11 times and trees 10 times. Furthermore, the lines illustrating floors on the building volume was also used.

4. Discussion and Conclusions

The result shows that participants were influenced in their judgments when they were presented with other building volumes before they judged the size of the new building volume. This is observed in case 1 in comparison with case 2 and 3. In case 1, the participants were presented with two larger volumes before their judgment, which made them perceive the volume as smaller then case 2 and 3. The larger volume seemed to provide a visual reference point, which in turn affected their judgment, a result in line with previous research (e.g. Kahneman, 2002). In case 2 where the volumes were smaller than the reference volume as compared to case 3 there was no significant difference. We speculate that this is due to the fact that the existing surrounding buildings are almost at the same level of height as the smaller reference volumes. Another interesting observation is that the respondents did not think that the previous volumes affected their judgment of the building volume, when the results clearly showed the opposite. We claim that this study has demonstrated the effects that reference points can have when conducting volume studies in virtual environments. Clearly, it is important to take this into account when using the VR-medium in real urban planning projects. A failure to do so risks biasing the judgment and outcome of the urban planning process. We acknowledge that this is a strong contention. However, given the fact some of the volumes used in this study have actually been used in real urban planning studies, were the use of the VR-medium was used in a similar way, we feel that this contention is justified. The first initial information, the large alternative, unduly

influenced how they reasoned about subsequent information. This result evidently shows that the initial visual information has a profound impact on participants' decisions, even though they know that the initial visual information had no validity. These results have implications for the use of VR-models in in actual decision-making settings. In this type of volume studies it could be agued that a more objective evaluation tool, such as visual impact analyses (Danese et al., 2009), could be combined together with the VR-medium. The visual impact analyses could give objective result of how the different design alternatives influence views and the streetscape. But also what viewpoints that is of important during judgment of the different design alternatives.

When doing volume studies in VR it is important to provide visual cues to the viewer such as the façades of the surrounding existing buildings and familiar details such as cars, people/avatars and trees. The viewer uses these features during spatial-reasoning for understanding sizes, which is in the line with research on spatial-perception (Biederman, 1990; Kosslyn, 1999).

To conclude, the assumption that people perceive and act on information in an un-biased fashion in VR-models being used for urban planning and building design can be seriously questioned. It is our experience that stakeholders and practitioners in this arena are not aware of some of the potential pit-falls associated with this use of this technology. The results from this study have implications for the use of VR-models in actual decision-making settings.

As mentioned in the introduction, the urban planning process has a lot of actors, all having their own more or less hidden agendas and interests. In this context it is important to bear in mind that the VR-medium could also be used as a tool for different actors to achieve different outcomes. All these issues have to be considered before the VR-medium can be seen as comprehensive decision-making tool in urban planning and building design.

References

Ambrose, P.: 1994, *Urban process and power*, Routledge.

Biederman, I.: 1990, Higher-level vision, *in* D. N. Osherson, S. M. Kosslyn, J. M. Hollerbach (eds.), *Visual Cognition and Action: An Invitation to Cognitive Science*, Vol. 2, MIT, Cambridge, MA, 41–72.

Buziek, G.: 2000, Legend designs for noninteractive cartographic animations, *Computers & Geosciences*, **26**(1), 21–28.

Danese, M., Nolè, G. and Murgante, B.: 2009, Visual Impact Assessment in urban planning, *in* B. Murgante, G. Borruso and A. Lapucci (eds.), *Geocomputation and Urban Planning*, Springer, 133–146.

Foo, P., Warren, W. H., Duchon, A. and Tarr, M. J.: 2005, Do humans integrate routes into a cognitive map? Map-versus landmark-based navigation of novel shortcuts, *Journal of Experimental Psychology: Learning, Memory, and Cognition*, **31**(2), 195–215.

Gigerenzer, G. and Selten, R.: 2002, *Bounded rationality: The adaptive toolbox*, MIT, Cambridge, MA.

Hall, A. C.: 1996, *Design Control: towards a new approach*, Butterworth Architecture Oxford.
Kahneman, D.: 2002, Maps of bounded rationality: A perspective on intuitive judgment and choice, *Nobel prize lecture*, **8,** 351–401.
Kenyon, R. V., Phenany, M., Sandin, D. and Defanti, T.: 2008, Accommodation and size-constancy of virtual objects, *Annals of Biomedical Engineering*, **36**(2), 342–348.
Kjems, E.: 2005, VR applications in an architectural competition: Case: House of Music in Aalborg, *Realitat Virtual a l'Arquitectura i la Construcció : Taller 2*, Khora II, Barcelona, 47–58.
Kosslyn, S.: 1999, Visual mental images as re-presentations of the world: A cognitive neuroscience approach, *in* J. Gero (ed.), *Visual and Spatial Reasoning in Design*, University of Sydney, 83–92.
Lange, E.: 2005, Communicating with the Public through Visualizations, *in* E. Buhmann (ed.), Trends in real-time landscape visualization and participation, Herbert Wichmann.
Loomis, J. M., Klatzky, R. L., Golledge, R. G. and Philbeck, J. W.: 1999, Human navigation by path integration, in R. G. Golledge (ed), *Wayfinding behavior: Cognitive mapping and other spatial processes*, Johns Hopkins University, 125–151.
Maarttola, I. and Saariluoma, P.: 2002, Error risks and contradictory decision desires in urban planning, *Design Studies*, **23**(5), 455–472.
Nikolic, D.: 2007, Evaluating relative impact of virtual reality components detail and realism on spatial comprehension and presence, Technical Report 52, Pennsylvania State University.
Plank, M., Müller, H., Onton, J., Makeig, S. and Gramann, K.: 2010, Human EEG correlates of spatial navigation within egocentric and allocentric reference frames, *Spatial cognition VII*, 191–206.
Riecke, B. E., Veen, H. A. H. C. and Bülthoff, H. H.: 2002, Visual homing is possible without landmarks: A path integration study in virtual reality, *Presence: Teleoperators & virtual environments*, **11**(5), 443–473.
Roupé, M., Johansson, M., Viklund Tallgren, M. and Gustafsson, M.: 2012, Using the human body as an interactive interface for navigation in VR models, *CAADRIA 2012, Beyond Codes & Pixels, Chennai, India*, **17**, 79–88.
Sigurdarson, S., Milne, A. P., Feuereissen, D. and Riecke, B. E.: 2012, Can physical motions prevent disorientation in naturalistic VR?, *Virtual Reality Workshops (VR), 2012 IEEE*, IEEE, 31–34.
Simon, H. A.: 1957, A behavioral model of rational choice, in H. A. Simon, Models of Man, Social and Rational: Mathematical Essays on Rational Human Behavior in a Society Setting, New York: Wiley.
Westerdahl, B., Suneson, K., Wernemyr, C., Roupé, M., Johansson, M. and Martin Allwood, C.: 2006, Users' evaluation of a virtual reality architectural model compared with the experience of the completed building, *Automation in construction*, **15**(2), 150–165.

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A SYNCHRONOUS DISTRIBUTED VR MEETING WITH ANNOTATION AND DISCUSSION FUNCTIONS

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Abstract. Owing to cloud computing Virtual Reality (VR), a note PC or tablet with no necessity of high spec GPU can be used for sharing of a 3D virtual space in a synchronous distributed type design meeting. In this paper, in addition to sharing a 3D virtual space for a synchronous distributed type design meeting, we developed a prototype system that enables participants to sketch or make annotations and have discussions as well as add viewpoints to them. We applied these functions to evaluate an urban landscape examination. In conclusion, the proposed method was evaluated as being effective and feasible. Operation is limited with one person, and more optional shapes should be prepared in future work.

Keywords. Spatial design; distributed synchronization; cloud computing; annotation; discussion board.

1. Introduction

In the spatial design field such as architectural design, urban design, and industrial design, a consensus-building process among a variety of stakeholders such as project executors, designers, neighborhood residents, users, and general citizens is required. Since it is necessary to share three-dimensional images to study design, 3DCG (3-Dimensional Computer Graphics), VR (Virtual Reality) and BIM (Building Information Modeling) systems have been developed. Design meetings using these systems have been traditionally held in the same-room and at the same time. In recent years, the mobility of people's activities, and cloud computing

technologies have become advanced in the modern age of information and globalization. Therefore, system developments and design trials of an asynchronous distributed type are used which means that stakeholders participate in the design process at different places and at different times (Maher and Simoff, 1999; Matsumoto et al., 2006). This allows expansion of communication opportunities, without a participant needing to worry about restrictions of space and time.

In a synchronous distributed type of environment, research on designs supporting a system for sharing three-dimensional virtual space exists. There is a system which allows designers to be physically immersed in their sketches and physical models, literally inside life-size, real-time representations of these, while sharing them remotely with another system of the same sort (Dorta et al., 2011). However, in this research, a framework for two or more stakeholders to participate in a design meeting of a synchronous distributed type using a standard spec PC is proposed. The data volume of the content of a design study is usually large. Therefore, when drawing 3D graphics with a client PC, a client PC with a high spec GPU (Graphics Processing Unit) is required (Gu et al., 2009; Shen and Kawakami, 2010). A standard spec PC cannot necessarily be used to participate in a design meeting. To solve this problem, Fukuda et al. (2012) presented the capability of a synchronous distributed type design meeting by using the cloud computing type VR (cloud-VR).

In cloud-VR, contents are transmitted by the video compression method of the H.264 standard. Commands about viewpoint change, plan changes, etc. of the three-dimensional virtual space on the client running on Microsoft Windows or Android OS or are calculated from the VR contents on a cloud computing type VR server. Then the calculated contents are displayed in real time on the client as a video, using the H.264 standard (Figure 1 and 2). One user can operate the virtual space of the cloud computing type VR, and the time for which it can be operated is less than 2 minutes. A user who wants to operate is allowed to operate it for less than 2 minutes. Therefore, this system has the following merits. 1) A highly efficient graphics environment is unnecessary in a client. Therefore, even at some sites or places where it is difficult to use a high-performance PC, it is still available on

Figure 1. Configuration of data transmission in Cloud-VR.

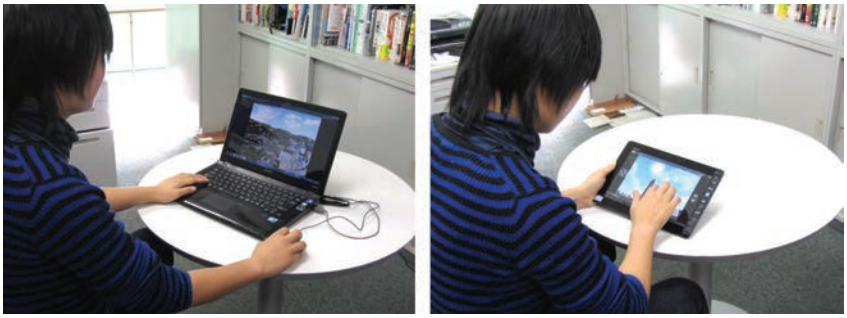

Figure 2. Use of Cloud-VR: Windows laptop (left), Android tablet (right).

mobile devices. 2) Plural participants can share a viewpoint, alternatives, or the VR setup in synchronization. 3) The VR application version or 3D contents are unified by the management on the server side.

Including the reported synchronous distributed 3D virtual space research (Fukuda et al., 2012), this study focuses on the annotation function – allowing freehand sketching in a 3D virtual space – and the discussion function – allowing stakeholders' real-time text discussion about a place in a 3D virtual space to facilitate study of a spatial design. In a word, the system can be used with a note PC or Android OS tablet with no necessity for a high spec GPU. Moreover, it can use 3D virtual space, and meanwhile necessary sketches or memos can be added in a synchronous distributed type design meeting.

2. System Design

2.1. ANNOTATION FUNCTION

Apparently, when using 3D virtual space to explore a design, people expect to be able to draw a sketch, and add figures and memos to the 3D virtual space. For instance, people would like to draw arrows or sketches to indicate their notes and changes to a plan or VR content in a co-design work. Thus, annotation can be defined as freehand sketching in a 3D virtual space in this paper. To annotate, an intuitive and seamless interface is necessary so that a designer's thoughts or a meeting may not be interrupted. Although a system based on pen interaction can already add annotations to VR contents and show them on a digital board (Fukuda et al., 2009), such a system is intended for a synchronous meeting where everyone is in the same place. Another system (Jung et al., 2001) has been executed by using Java3D and VRML (Virtual Reality Modelling Language), but this is available for the asynchronous distributed type meeting by using 3D virtual space. Above all,

we are aiming to develop a system that can be applied to a synchronous distributed meeting.

Annotation can be used not only to include 2D information but also to identify a certain position in 3D virtual space. In addition, a virtual camera must be set up to describe annotations. The requirements for annotation are below.

- Save an annotation in the form of XML. Each annotation has a category, a project id, and content information.
- An annotation can be open and closed in the 3D virtual space.
- In the Closed state, a new icon is put at the position where a new annotation is placed. Users can open it by clicking on the icon.
- In the Open state, install a virtual camera placed at the position of an annotation and show its content. When the VR virtual camera moves back from the position of the annotation, the content of the annotation gradually becomes transparent until it disappears completely.
- In the Edit state, place a camera at the position of an annotation, and show its content. While editing in a 3D virtual space, no other operations are allowed.
- To close the window, select whether to save or cancel changes generated by the editing process
- An annotation can be copied and cancelled.
- When opening or editing an annotation, the background is supposed to be translucent for easy editing operation.

Also, a schema of an annotation requires the following conditions.

- Show the schema in 2D.
- Enable drawing of freehand sketches and/or basic shapes.
- Enable clicking on shapes (a polygon, circle, textbox, etc.) and select one.
- After selection of a shape, enable users to change its colour and transparency.
- After selection of a shape, enable users to change the colour, size and transparency of the border line.
- After selection of a shape, allow movement of the shape by dragging a mouse.
- Resize the shape if a form is resized or a vision field is changed.

2.2. DISCUSSION FUNCTION

In synchronous face-to-face meeting, sharing a 3D virtual space, oral discussion is carried out by using video conferencing systems. However, the conversation will be lost after it finishes.

On the other hand, although a common text-chat-system can store the contents of a conversation, it is difficult to specify the position and range of the virtual space. In order to solve these problems, Fukuda and Kaga (2005) presented a system linking the subject of a discussion to its position in the 3D virtual space.

However, it is an asynchronous distributed type, and only a limited point can be specified. So a certain range besides one point is also necessary as a discussion area.

The discussion function developed in this paper can display a discussion board upon a point or an area whose radius can be defined by a user. Furthermore, since it is difficult to discover a discussion board in the wide range of a 3D virtual space, adding viewpoint information with a discussion board to show the discussion board quickly is a useful feature. The following instructions describe the designed functions and concepts.

- Create a new discussion or its area: a user creates a new discussion board at any point in a 3D virtual space. The discussion board has a category, a project ID, longitude, latitude, a radius of the discussion area (0 in some case) and a password.
- View an existing discussion or its area: view the discussion or its area which has already been created.
- Edit an existing discussion or its area: edit the discussion or its area which has already been created. “Edit” here means to revise the discussion board information, including adding, editing, and deleting comments as well.

3. Verification

A prototype system was implemented based on the specifications described in section 2. Next, although the client needed to load annotations and/or discussion data from a server to display or update them for technical verification, the latency in this regard was small, and the system was suitable for use in a synchronous distributed meeting.

A case study of an urban landscape examination was given (Figure 3).

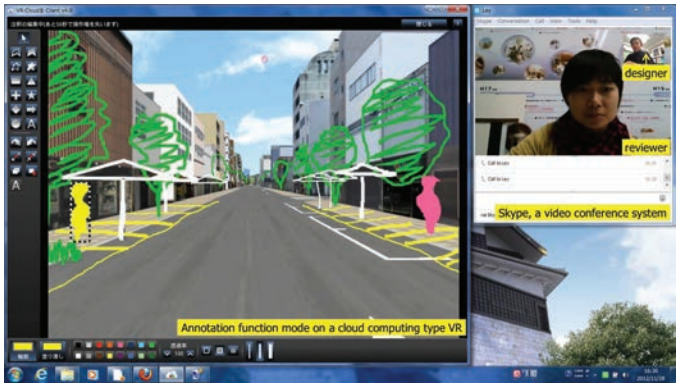

Figure 3. Screenshot of a synchronous distributed design meeting by using cloud-VR.

Supposedly, there was an imaginary VR project which was a renovation plan in Shimonoseki Buzenda shopping street (100m width, 350m extension), Shimonoseki City, Yamaguchi Prefecture, Japan. The content of cloud-VR was shown on a Windows laptop PC or Android OS tablet in the synchronous distributed meeting. Meanwhile, design work was being performed along with using a video conferencing system such as Skype. Combined results from the examination led to the following conclusions.

3.1. ANNOTATION FUNCTION

Figure 4 shows the annotation function's flow, while Figure 5 shows the capture of a created annotation. The main menu for annotation edit provides functions as below.

- Button on the top right: cancel and save the edited operation
- Left button: tool buttons for drawing and editing a shape
- Bottom button: Select colour and set transparency or frame when drawing shapes.

In this imaginary project, typical work using the annotation function is described. Suppose a street has to be renewed and it must widen its sidewalk, a draft of where to place trees must be made, street lamps and benches have to be place, all taking account of many factors such as safety, function, security and infrastructure influence. Furthermore, according to the draft, tree species, lighting and bench forms would be selected and determined. The VR content can put a line around the areas which need to be revised, show what has to be moved using arrows, or note detailed information. An enclosed line enables users to highlight

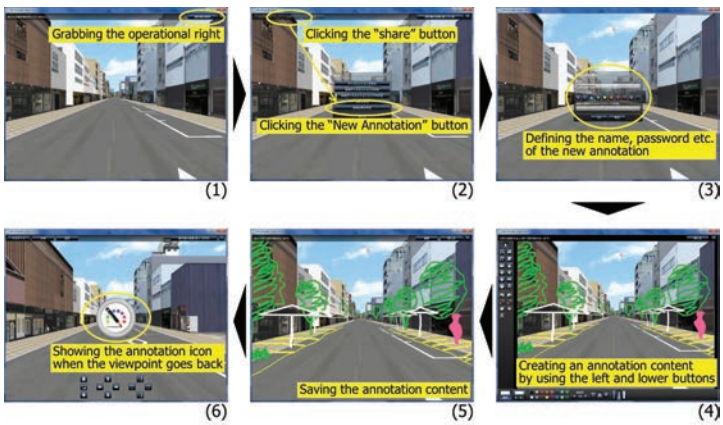

Figure 4. The flow of the annotation function.

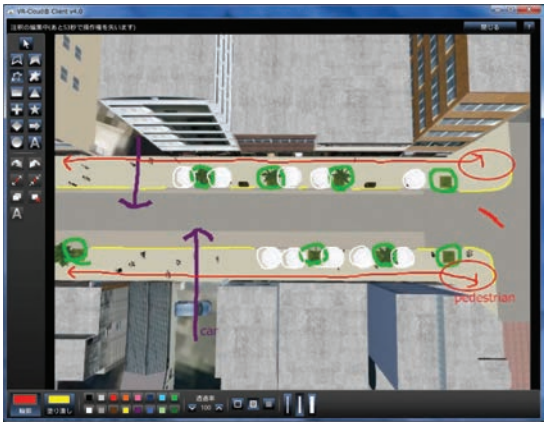

Figure 5. The main annotation menu on a cloud-VR.

important things to be done. Also, participants are able to share the content intuitively. On the other hand, there are still many unclear problems, as described below.

- Editing of annotations is limited to only one person. That is, two or more participants cannot use the annotation function simultaneously right now. Nor can the same one be opened or re-edited before other users have closed it.
- Contents of annotations need to link with the displayed plan. In a design process, several plans are registered into VR, and usually discussed by comparing them. The developed annotation function was realized to connect viewpoint information. However, no link has yet been implemented between the annotation content and the displayed design alternative. Therefore, the annotation content sometimes does not match the displayed design alternative to which it should correspond.
- Since orthographic projection on VR is not yet available, it is difficult to sketch correctly in accordance with the scale.

3.2. DISCUSSION FUNCTION

The flow of the discussion function is shown in Figure 6, and Figure 7 is an icon showing the subject area being discussed.

The typical work using the discussion function was stated in this imaginary project. In order to offer rest areas, a small park is preferred to be located in a shopping street because it is easy for people to gather there. To explore a design for that, designers may set up a discussion board, and questions may arise such as from which direction people visit the shopping street or which intersection gathers the largest number of people. Then consultants who understand the amount of

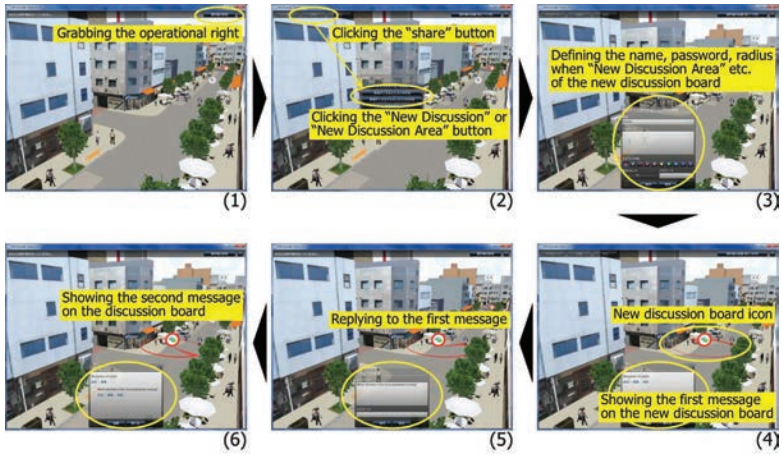

Figure 6. The flow of the discussion function.

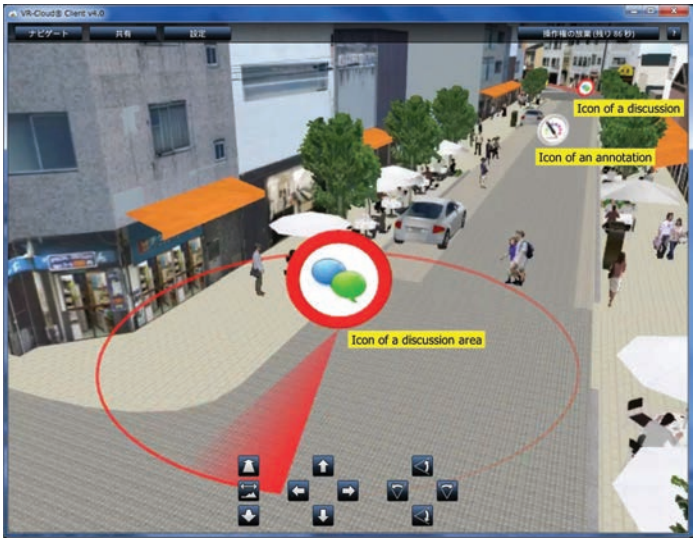

Figure 7. Icons of both the annotation and discussion functions.

pedestrian traffic give the right answers. Next, designers receive those answers and discuss the position of the small park. Because the discussion area function has been developed in this study, it is possible to specify the approximate area used for discussion. However, the challenges below remain.

- Editing of discussions is limited to only one person. That is, two or more participants cannot edit discussion function simultaneously right now. Nor can the same discussion be opened or re-edited before other people have finished typing and then closed it. As result, it is necessary to inform participants of this procedure during a video conferencing system.
- The best discussion board to use when spatial information is not necessary should be considered. In this study, the Skype chat system is used to discuss things without spatial information.
- A discussion area cannot be defined except round a shape. On the other hand, it became clear that the discussion area is not limited to a circle shape during the design study. For instance, discussion areas defined by the vertical surface of a building façade, the line of a pedestrian way, or a polygonal shape created by freehand drawing should be implemented.

4. Conclusion

This study has a designed annotation function and discussion function which are essential for a 3D virtual space in order to allow synchronous distributed meetings. A prototype system was developed and verified through a case study. The contributions of this research are as follows:

- The annotation function seamlessly enables users to draw sketches and shapes and add memos in a 3D virtual space by freehand. Because viewpoint information is also saved when writing an annotation, it has proved easy to reproduce. Problems remain, such as that annotation editing is limited to one person, so several people cannot edit the annotation function simultaneously. Also, the contents of annotations need to link with the displayed plan.
- The discussion function enables users to combine the information from a point or a certain area with textual discussions on a 3D virtual space. Future work on the discussion function should address the issues that discussion editing is also limited to only one person and two or more people cannot type discussions at the same time. Additionally, it is necessary to be able to specify a discussion area in various shapes.

It is necessary, as future work, through experiments involving meetings of three or more persons, real design project meetings, international meetings, etc. to investigate the possibilities for synchronously distributed VR meetings.

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References

Dorta, T., Kalay, Y., Lesage, A. and Perez, E.: 2011, Comparing Immersion in Remote and Local Collaborative Ideation through Sketches: A Case Study, *Proceedings of the 14th international conference on Computer Aided Architectural Design (CAADFutures 2011)*, 25–39.

Fukuda, T. and A. Kaga: 2005, Development of 3DBLOG: VR-BLOG System Which Supports Network Collaboration, *Proceedings of the 9th Iberoamerican Congress of Digital Graphics SIGraDi 2005*, 327–332.

Fukuda, T., Kaga, A., Izumi, H. and Terashima, T.: 2009, Citizen participatory design method using VR and a Blog as a media in the process, Int'l Journal of Architectural Computing, 7(2), 217–233.

Fukuda, T., Taguchi, M., Shimizu, A. and Sun L.: 2012, Availability of a distributed and synchronised type meeting by using cloud computing type VR for spatial design study, Proceedings of the 17th International Conference on Computer Aided Architectural Design Research in Asia CAADRIA2012, 203–210.

Gu, N., Nakapan, W., Willians, A. and Gul, L. F.: 2009, Evaluating the use of 3D virtual worlds in collaborative design learning, *Proceedings of the 13th international conference on Computer Aided Architectural Design (CAADFutures 2009)*, 51–64.

Jung, T., Gross, M. D. and Do, E. Y.-L.: 2001, Space Pen: Annotation and sketching on 3D models on the Internet, *Proceedings of the Ninth International Conference on Computer Aided Architectural Design Futures*, 257–270.

Maher, M. L. and Simoff, S.: 1999, Variations on a Virtual Design Studio, *Proceedings of Fourth International Workshop on CSCW in Design*, 159–165.

Matsumoto, Y., Kiriki, M., Naka, R. and Yamaguchi, S.: 2006, Supporting Process Guidance for Collaborative Design Learning on the Web; Development of "Plan-Do-See cycle" based Design Pinup Board, Proceedings of the 11th International Conference on Computer Aided Architectural Design Research in Asia *CAADRIA200*6, 72–80.

Shen, Z. and Kawakami, M.: 2010, An online visualization tool for Internet-based local townscape design, *Computers, Environment and Urban Systems*, 34(2), 104–116.

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DIFFERENCE BETWEEN A PHYSICAL MODEL AND A VIRTUAL ENVIRONMENT AS REGARDS PERCEPTION OF SCALE

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Abstract. This paper focuses on differences of spatial reasoning capacity observed by using a physical model and a virtual reality (VR) system, and specifically emphasizes perception of the scale of space. While respondents viewed a physical model and a VR system, a questionnaire was used to objectively evaluate these and establish which was more accurate in conveying object size. As a result, it was acknowledged by the respondents that the physical model performed more accurately and quickly. Subject to further validation, we expect the physical model to offer great utility to develop new digital media in the future.

Keywords. Spatial reasoning capacity; scale perception; physical model; virtual reality; questionnaire.

1. Introduction

Aside from text and diagrams, three-dimensional visualization media, such as physical models, CG (Computer Graphics) and VR (Virtual Reality), are used to confirm space or volume in the design and presentation of architectural and urban fields (Dorta and LaLande, 1998; Belcher and Brian, 2008; Fukuda et al., 2009). The physical model and CG/VR can display in arbitrary viewpoint so that they are effective on the occasion of discussion and examination. A physical model has the advantages that several people can observe it from any viewpoint simultaneously and see the picture of a whole depicted city at once. On the other hand, there are still some difficulties if considering the pedestrian viewpoint and limits of representation caused by the small scale. CG/VR is a media using a virtual environment (virtual media) and is easy to show an eye-level viewpoint of pedestrians and drivers as well as other people and vehicles, and it can simulate such effects as solar

radiation in a dynamic way. On the other hand, problems remain, such as possible viewpoints normally limited to one place and intangibility as well. Due to the distinct characteristics of the physical model and CG/VR as mentioned, they are now used together in construction sites or for planning or design (Tokuhara et al., 2010). For instance, at the stage of planning and design, a physical model is used in the first conceptual expansion phase, and then CG/VR is used in the other convergent design phase.

The reasons for combining the physical model and VR, include ease of fabrication, manipulation of users, cost and labour. Meanwhile, the differences based on a physical-media model and virtual-media VR may also be a factor. Spatial reasoning capacity refers to understanding the shape, size, location and texture of an object or space. However, people have to use many clues and think carefully in order to understand it. Moreover, how to use those clues is completely unexplained, as a result of the complexity caused by distances to the object and observation conditions.

1.1. PREVIOUS STUDIES

Siitonen (1995) used and compared a walk-through VR and an endoscope-photographing model method, and verified which one was better in manipulation, lighting and spatial reasoning capacity through visual observation of outcomes and interviews with participants. The verification results, however, lacked objectivity because they had not been quantified. In addition, as a study of spatial reasoning capacity using media systems, Witmer and Singer (1998) implemented a questionnaire on control, sensory, distraction and realism factors contributing to a sense of presence in VR. Furthermore, a new questionnaire was conducted by Lessiter and Freeman (2001) which addressed sense of physical space, engagement, ecological validity and negative effects factors. Also, spatial reasoning capacity was compared in the results from Imax2D, Imax3D, computer games and videos and calibrated principal components analysis. However, according to the above studies, the respondents, even in another scene, could still experience a sense of “being there” elicited by VR but can hardly do so with a real-media model.

1.2. PURPOSE OF THIS STUDY

This paper focuses on differences in spatial reasoning capacity observed by using a physical model and a VR system, and specifically emphasizes perception of the scale of space. While respondents viewed a physical model and a VR system, a questionnaire was used to objectively evaluate these and establish which was more accurate in conveying object size.

2. Experimental Methodology

The experiment showed respondents the same object that was depicted by both the physical model and VR alternatively, and required three grouped categories: the first was a height comparison of the relative size, the second was the absolute size of one building, and the third was the scale of the object. The object in this experiment was part of a shopping area (square 100m) in Buzenda, Shimonoseki City, Yamaguchi Prefecture, Japan, where there are about 30 buildings within 3~30m height on flat ground. Buildings and ground used a monochrome texture of white and grey so that it was impossible to judge the size from the building floor height or road width. A digital model for VR was created using Autodesk 3ds Max 2010. The physical model was derived from VR digital data and created by a 3D printer.[1]

As a way of observation, in order to avoid bias from the respondents' previous experience of VR manipulation, which could affect the evaluation, the VR camera was set up at an angle of 45-degree from the ground and captured a fly-through movie (VR movie as below) which circles around from a bird's-eye view.[2] The respondent sits at a 600mm distance from the VR display (21 inches) and viewed it horizontally. It was not expected that a respondent would look differently at the VR and physical model, so we tried to match these two media in terms of size, viewpoint angle and brightness. Al so, the physical model was mounted on a turntable that could rotate 360 degrees (Figure 1).

At the beginning of the experiment, the respondents were told that the depicted physical model and VR movie content were part of one city in Japan but they were

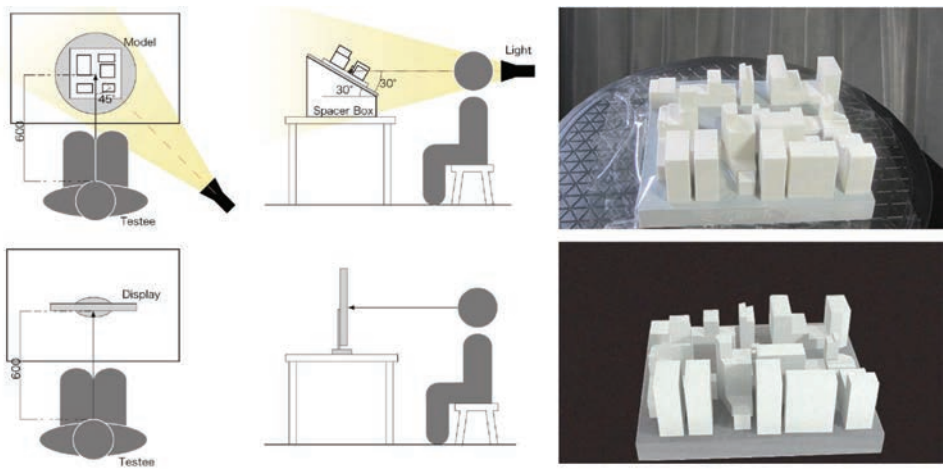

Figure 1. Position of a respondent and media (up: physical model, down: VR).

not informed of its name since we wished to reduce the effects of different levels of knowledge or preconceptions related to the location at this time. The physical model and VR movie respectively span one time before the questions were presented.

The first question was the height comparison of buildings. The questioner showed the physical model and VR movie in sequence and indicated two buildings with different heights in the object. The respondent was then required to answer "which one is higher". In order to avoid impression change generated by pointing out the building, each media was presented from a still viewpoint. There were four pairs of presented buildings and the real height differences were 1.5m (building A: 6.5m, Building B: 5m), 5m (A: 15m, B: 10m), 10m (A: 18m, B: 28m), and 20m (A: 30m, B: 10m). Every respondent viewed the buildings at a 30-degree angle. Figure 2 shows the pairs for height comparison of buildings. Figure 3

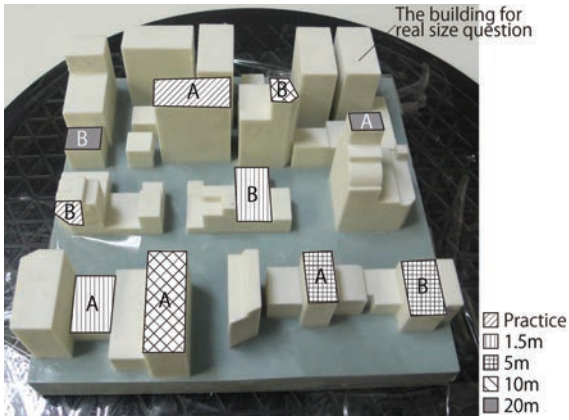

Figure 2. The building pairs for height comparison.

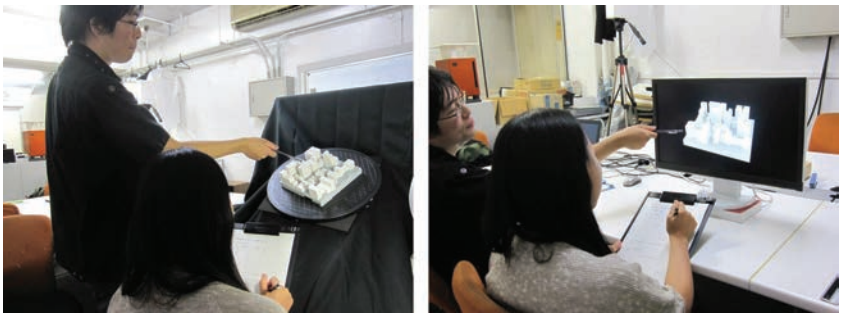

Figure 3. Experiment image (left: physical model, right: VR).

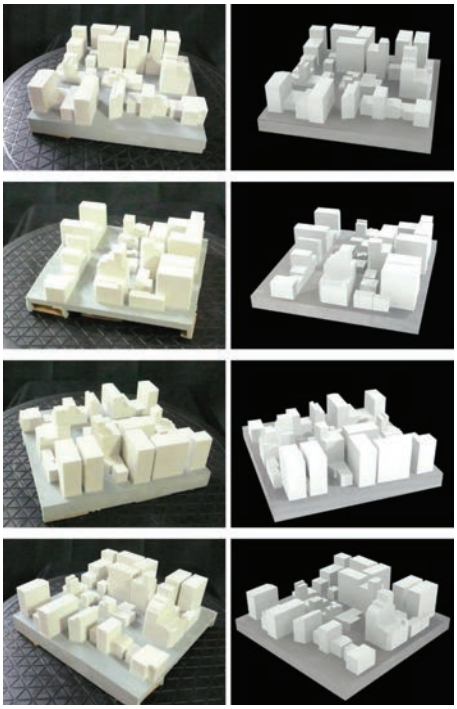

Figure 4. Every viewpoint requiring the height difference. (Up: 1.5m, upper middle: 5m, lower middle: 10m, down: 20m).

shows the experiment image and Figure 4 illustrates every viewpoint related to the question on the height difference.

The second question was about the real size of one building. The questioner presented a physical model and VR movie in sequence and asked the responds to judge the real size of one building (see Figure 2, “the building for the real size question”). Then, the respondent answered the question “how many millimetres in the physical model” and “how many meters in the virtual space”.

The third question was on the scale of the physical model. As each question was answered, the response time was measured by a stopwatch until the end of the final answer.

3. Experimental Results

Experiments were administered on September 24 (Saturday) ~ 30 (Friday) 2011. The respondents were a total of 24 students, and all were aged in their 20s, among which

16 were male and eight were female. Additionally, in order to avoid their impression being changed by the presented sequence of the media, half of the sample experienced the physical model first while the other half experienced the VR first.

A five-point scale was chosen as the response option for the height comparison of buildings. 1 = A is high, 2 = A is rather high, 3 = same, 4 = B is rather high, and 5 = B is high. According to the real height difference, the correct answers were these: number 1 was assigned 1.5m, 5m, 20m and number 5 was 1m and 10m. The mean and variance of the absolute value of the difference in a correct answer and the response in each question were calculated. The response time was set as the average response time of the height comparison of buildings. To assess the real size of one building and the scale of the physical model, (i) assign H_a (mm) the height on physical model, (ii) H_b (m) the one on VR, and (iii) H_c (m) the product of building height and scale. H was the correct answer, which was 50mm for case (i) and 25m for case (ii), (iii). The rate of deviation (see equation 1) was defined for each H_a, H_b, H_c and H and the mean and variance of these were calculated. Exploratory analyses were performed based respectively on presented media order, respondents' experience, gender as well as the sample.

$$D_x = |1 - H_x / H|_{(x = a, b, c)} \tag{1}$$

3.1. SAMPLE ANALYSIS

Table 1 shows the correctness in referring to the height comparison. First of all, everyone correctly responded to the height differences of 10m-, 20m-case on the physical model and the 20m case on VR. Therefore, in these cases, tall buildings were evaluated accurately. Then, it was clearly found that responses elicited by the

Table 1. The correctness referring to the height comparison (N = 24).

Height difference(m)	Medium	Correct	Mean	|Mean–Correct|	Variance
1.5	Physical model	1	1.29*	0.29	0.71
	VR	1	1.71	0.71	1.54
5	Physical model	1	1.13**	0.13	0.19
	VR	1	1.92	0.92	0.99
10	Physical model	5	5.00**	0	0
	VR	5	3.96	1.04	1.29
20	Physical model	1	1.00	0	0
	VR	1	1.00	0	0

Non*: no statistical significance, *: 5%, **: 1%

Table 2. Average response time (N = 24).

Height difference(m)	Physical model (s)	VR (s)	Physical model-VR (s)
1.5	2.01**	3.29	–1.28
5	2.48**	4.38	–1.90
10	1.98**	3.85	–1.87
20	1.55*	2.38	–0.83

Non*: no statistical significance, *: 5%, **: 1%

Table 3. The real size and physical model's scale based on presented media order (N = 24).

	Physical model (D_a)	VR (D_b)	Physical model×scale (D_c)
Average rate of deviation	22.50%	72.20%	130.30%
Variance	0.17	1.21	5.78

physical model are more accurate than those by VR in the case of 1.5m within statistical significance –5% (5%), and 5m, 10m within significant difference-1% (1%).

Table 2 summarizes some results for response time. Timed responses to the physical model were shorter than those by VR in the case of 1.5m, 5m, 10m within 1%, and 20m within 5%.

Consequently, the physical model, not VR, tends to allow quicker and more accurate comparison of building height.

Table 3 indicates the results for the real size and physical model's scale. It turned out that the physical model had the lowest rate of deviation and smallest variance among respondents for three items in Table 3, namely D_a, D_b and D_c. On the other hand, the variance in scale evaluation shown by the sample was quite large, and moreover, the value of rate of deviation in the list of physical model×scale was larger than VR.

3.2. PRESENTED MEDIA ORDER ANALYSIS

Response data divided by each height difference were entered into a t-test analysis. As shown in Tables 4 and 5, there was no significant difference in correctness or response time, which means the impression change was not related to whether a physical model or VR was used as previously discussed in section 2. The response-time difference on the other hand was small for all items if the physical model was first compared to VR. One reason for this was that the participants

Table 4. The correctness referring to the height based on presented media order (N = 24).

Height difference(m)	Medium	Correct	Mean (Physical model first)	Mean (VR first)	Variance (Physical model first)	Variance (VR first)
1.5	Physical model	1	1.08	1.50	0.08	1.15
	VR	1	1.42	2.00	0.41	2.31
5	Physical model	1	1.00	1.25	0	0.33
	VR	1	1.83	2.00	1.31	0.62
10	Physical model	5	5.00	5.00	0	0
	VR	5	4.25	3.67	0.85	1.44
20	Physical model	1	1.00	1.00	0	0
	VR	1	1.00	1.00	0	0

Non*: no statistical significance, *: 5%, **: 1%

Table 5. Response time based on presented media order (N = 24).

Height difference(m)	First Media presented	Physical model (s)	VR(s)	Physical model-VR(s)
1.5	Physical model	0.96	1.43	–0.46
	VR	1.68	2.94	–1.26
5	Physical model	0.72	1.35	–0.64
	VR	2.12	3.38	–1.26
10	Physical model	3.00	3.04	–0.04
	VR	1.58	3.64	–2.06
20	Physical model	0.60	0.60	0.00
	VR	1.43	2.87	–1.44

Non*: no statistical significance, *: 5%, **: 1%

grasped the whole picture during their VR experience because they had experienced the physical model before. In addition, the consequences did not vary by gender.

4. Conclusion

This paper aimed to emphasize perception features of spatial scale in the spatial reasoning capacity field. It managed to assess whether a physical model or VR was more accurate and easier to use when respondents evaluated an object's size. Therefore, using a section of a city in Japan depicted by a physical model and VR,

an experiment was conducted and 24 respondents answered questions regarding a height comparison, the real size, and physical model's scale. As a result, it was acknowledged by the respondents that the physical model performed more accurately and quickly.

A comparative experiment is required to match conditions identically, except for variables. So in this study, the proposed physical model and VR were designed to be the same size and to have the same façade in order to define features of spatial dimension. To ensure they were the size same, a physical model was created from digital data by using a 3D printer employing RP (Rapid prototyping) technology. If a physical model is traditionally made by hand and VR is made by CAD separately, it is very hard to ensure they both have the same size. Therefore, information and communication technology facilitates the preparation of such environmental experiments.

The future work should research the difference of size as perceived by professionals and non-professionals in architecture since citizens' participation in the planning and design process has been increasing along with the use of physical models or VR on such sites. In this study, although nine of the people in the sample had some practical design experience in architecture, urban and civil engineering, this was of no special note. One of the reasons was that all respondents were students whose relative experiences was no more than three years, which was not enough to cause a difference.

Acknowledgements

We thank all the participants for their generous assistance in conducting the experiment.

Endnotes

1. The proposed physical model was made by ZPrinter650, and had a high level of accuracy in transferring digital data to a physical model.
2. VR was performed by stereovision in the preliminary experiment (Olympus Power3D Media Player with 3D-Glass). Because the internal definition in the computer for VR was the full-size scale, the stereoscopic effect could not be seen. Therefore, stereovision was not employed in this experiment.

References

Belcher, D. and Brian J.: 2008, MxR: A Physical Model-Based Mixed Reality Interface for Design Collaboration, Simulation, Visualization and Form Generation, *Silicon + Skin: Biological Processes and Computation: Proceedings of the 28th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, 464–471.

Dorta, T. and LaLande, P.: 1998, The Impact of Virtual Reality on the Design Process, *Digital Design Studios: Do Computers Make a Difference?: Proceedings of the 18th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*, 138–163.

Fukuda, T., Kaga, A., Izumi, H., and Terashima T.: 2009, Citizen participatory design method using VR and a Blog as a media in the process, *Int'l Journal of Architectural Computing*, **2**(7), 217–233.

Lessiter, J. and Freeman, J.: 2001, A Cross-Media presence questionnaire: The ITC-Sense of Presence Inventory, *Presence, Teleoperators and Virtual Environments*, **10**, 282–297.

Siitonen, P.: 1995, Future of endoscopy updated, *2nd EAEA Conference*, 69–73.

Tokuhara, T., Tomohio, F., and Nobuyoshi, Y.: 2010, Development of a City Presentation Method by Linking Viewpoints of a Physical Scale Model and VR, *FUTURE CITIES: 28th eCAADe Conference Proceedings*, 747–754

Witmer, B.G. and Singer, M. J.: 1998, measuring presence in Virtual Environments: A Presence Questionnaire, *Presence, Teleoperators and Virtual Environments*, **7**, 225–240.

PARAMETRIC DESIGN

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EXTREMELY HEAVY AND INCREDIBLY LIGHT

Performative assemblies in dynamic environments

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Abstract. This research addresses the design and negotiation of two kinds of assemblies that are similar in topology but fundamentally different in performance. Firstly, Topological Interlocking Assemblies (TA) are made of solid elements. Their overall structural integrity relies on each element being kinematical constraint by its neighbours. Secondly, Bell Kites, similar in topology but fundamentally different in performance these kites are made of clusters of tetrahedrons. While TA are heavy, massive and exposed to gravity Bell Kites are super light and dominantly driven by wind forces. These two instances formulate the opposing ends of a spectrum in which a new system, one that is capable of covering the full range of performance, is developed and re-conceptualized in architectural context. The research seeks design-innovation by scrutinizing systems that are not yet part of the architectural ecosystem. Mapping out their performative characteristics and developing their spatial and programmatic potential through conscious design moves explore the potential for architectural applications. The work presented in this paper is the result of a design research studio of the Architecture and Performative Design Class at the Staedelschule in Frankfurt.

Keywords. Topology; interlocking; bell kite; modular; adjacency.

1. Introduction

With ‘Extremely Heavy and Incredibly Light’ we seek to merge two modular systems, which have similar geometrical properties but greatly differ in their

performance: Topological interlocking originates from ancient timber construction and has only recently been rediscovered by material scientist. Bell Kites were a break-through in manned flight as they overcame the scaling laws usually limiting kites in size and potential payload. They also laid the ground for uniform space-frame structures later promoted by Konrad Wachsman and Buckmintser Fuller. In our design research we investigated the architectural potentials of a hybrid system.

In this paper we first describe the research on topological interlocking assemblies and their computational design and digital fabrication. This 'heavy' part of the research is followed by a presentation of parametric kites based on Bell's approach. After exploring the two extreme ends of the overall spectrum we present hybrid systems as integrated architectural design proposals.

2. Topological Interlocking Assemblies (TI)

Topological Interlocking Assemblies (TI) consist of many solid objects (Figure 1). Cubes or tetrahedrons are assembled in a way that they kinematically constrain each other. Every building block is locked by its neighbours and locks them.

This mutual affect dispossesses the system of any translational or rotational freedom. Only the specific geometry of the elements and the topology of the assembly create structural coherence. Adjacency replaces glues or mortar. The structural principle of TI resembles the reciprocal frame, a widely used construction techniques for ancient Asian timber structures but also known by medieval building master. In the 17th centaury Stereotomy, the art of cutting stone and creating the necessary drawing (traits) allowed the creation of geometrically complex building blocks and interlocking systems (Evans, 1995). The new technique made it possible to transfer the technique from linear timber elements to massive, solid stones. In 1699 Joseph Abeille patented his 'Flat Vault' a planar assembly of truncated tetrahedron shaped stones. The interlocking system was supposed to span without the curvature of a vault. Only the way the building blocks interlock refers to medieval vaults with keystones. The Flat Vault never became a successful construction system but material scientists rediscovered it very recently and revealed

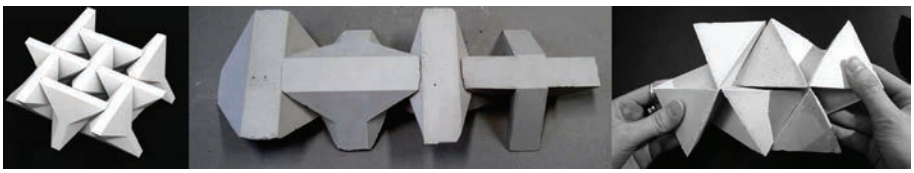

Figure 1. Examples of Topological Interlocking Assemblies.

its potential in a different scale (Estrin et al., 2011). Planar materials fail through propagating cracks. TI are fragmented already. Local cracks cannot propagate throughout the entire system.

3. Bell Kite Assemblies (BA)

Bell Kites are space-frame like structures based on tetrahedral cells. These cells can be cluster homogeneously or fractal-like into various forms including plates, bars, cubes, rings. Alexander Graham Bell invented these structures during his research into manned flight between 1895 and 1910. He challenged the notion of kites at the time which had the shortcoming of getting over-proportionally heavier when increasing the surface area thus putting an absolute limit on the size of kites. He discovered a concept of a cellular kite that overcame this problem and gave a way for carrying payload resulting in the first manned flight on a structure that was heavier than air.

4. Design Context and Methodology

In the context of this project we studied TI and BA as two extreme ends of a spectrum. TI as a massive solid system exposed to gravity and thrust suitable for retaining constructions massive walls and slabs. BK, in contrast, explore other aspects of performance and open up even more design opportunities. The methods to investigate and explore both systems are different and only partly overlap.

4.1. PARAMETRIC EXPLORATION

Parametric design techniques allowed us to differentiate the single elements within both assembly types to achieve more non-repetitive configurations. The geometric affinity between both was reason enough to explore the potential to merge the systems. Our research scrutinized the architectural potential of historic systems re-visited with contemporary design and analysis tools.

4.2. SIMULATION

Although both assembly types heavily rely on geometric properties, their performance cannot be revealed through mere geometric representation. Both systems are in some respect over-performing, leaving room for design innovation and including performative aspects that go beyond the primary function of the initial system. The TI can be altered in shape and reduced in volume as long as the contact faces between cells are maintained. BK generate an excess of lift thus leaving room for altering the effective area of each cell in favour for other criteria.

For TI we simulated the interaction of solid blocks under the influence of gravity with rigid bodies in animation software. The model served as a qualitative investigation rather than delivering exact numbers of forces and stresses. It nevertheless helped to understand the principal behaviour of parametric TI's. Conventional structural analysis tools used in the design of architectural structures are not capable to model the contact forces between adjacent building blocks. Brocato and Mondardini (2010) describe an approach of mechanical computation of Abeille's Flaut Vault transferred into a geodesic spherical assembly. Cast3M is used for a finite element model. The interfaces are modelled as joints that transfer compression forces and tangential forces limited by friction. The elements stay separate and glide on each other. The discrete element method (DEM), designed to simulate granular and discontinuous materials, is considered as another method to achieve precise numerical results. Nevertheless in our early design exploration we relied on available and quick-to-acquire qualitative simulations.

The kite dynamics of BK and their non-linear behaviour were simulated in animation software using a physics and cloth engine. The set-up aimed at establishing whether a given kite design would generate enough up-lift to get the kite airborne. These designs were then prototyped and flight tested. Only through physical testing the fine tuning of the bridle was set to the wind conditions of the day. The actual strength of joints and linear members could only be optimised by physical tests as the digital simulation was lacking the analysis of internal forces.

4.3. DIGITAL FABRICATION

The facetted polyhedra shapes are un-foldable, which allowed us to fabricate them from sheet material after unrolling in the modelling software (Figure 2). We established the technique for formwork production of TI elements and seamlessly transferred it to cut the canvas of the kites. In addition we 3d-printed only KI space

Figure 2. Unfolded cut pattern for TI mould (left). Laser-cut kite membrane and node.

frame nodes and TI elements that could not be unfolded or needed to be made from solid material.

5. Topological Interlocking Assemblies for Architectural Constructions

Within the above-described technological and methodological context we investigated TI as an architectural construction system. We differentiated the modules by manipulating the surface area of their adjacency, which yielded porosity in formerly sealed assemblies (Figure 3). Furthermore a parametric description of the element increased the geometric freedom beyond mere planar configurations. TI's could now become walls, ceilings, slabs, vaults or intrinsically interlocked sculptures with very ambiguous structural behaviour. Every avenue of exploration was not only investigated by computational modelling and simulation but also tested as physical prototypes. The actual making of the artefacts became a prototype of production workflows like mould making and casting. The research is extensively described in a previous paper (Tessmann, 2012).

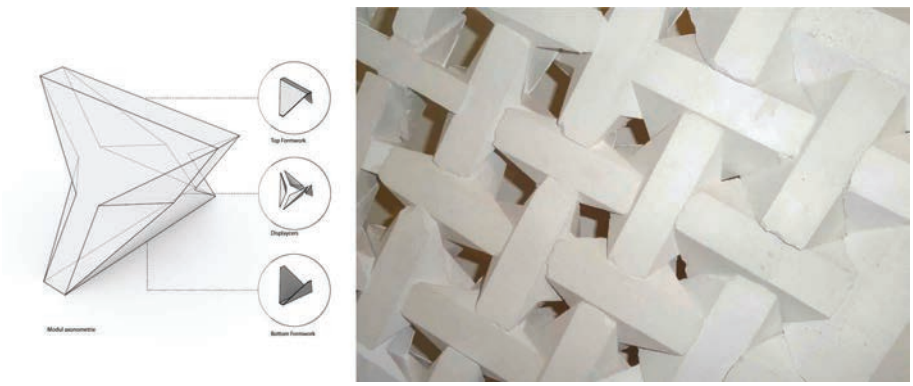

Figure 3. Truncated tetrahedra assembled as a porous wall/slab system (Design: P. Mecke).

6. Bell Kite design and Flight Test

Based on the TI assemblies we developed the modular kites and replaced adjacent surfaces between elements by nodal connections. The massive TI dissolves into a lightweight skeleton/canvas system (Figure 4). The forces change from static (gravity) to dynamic (multi-directional wind).

After studying the properties of BK in their initial design and gaining expertise in their behaviour new designs were proposed. As with the TI system the aim

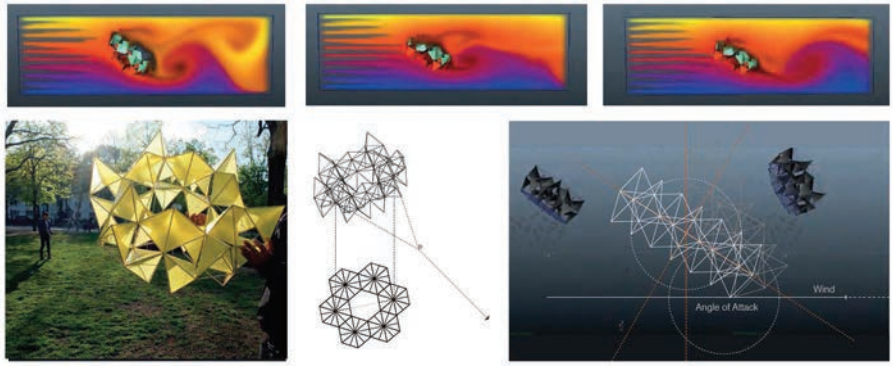

Figure 4. A kite based on hexagonal cells designed by Donlaporn Chanachai.

was to find architectural applications. Based on the findings this lead to the systems for large spanning roof structures and canopies where the potential uplift forces could overpower the dead-loads of the system. Also the self-stabilising properties of kites where higher wind forces lead to an overall more stable condition where developed into spatial and architectural features.

7. System Integration

Alexander Graham Bell's kites inspired not only the work of Max Mengeringhausen, Konrad Wachsmann, or R. Buckminster Fuller but also evolved in his own work into lightweight architectural structures. In 1907 he erected an 80-foot observation tower on his own premises. Four tetrahedral-celled trusses act as legs that intersect on the top to carry an observation platform (Wachsmann, 1959).

Bell paved the way for lightweight vector-active structures in architecture which where initially designed to fly. In our research we seek to further integrate the tetrahedral approach into a broader system: from flying, to lightweight, to extremely heavy interlocking assemblies; bound together by an overarching principle of geometrically related parametric building blocks. We developed two methods of integration in a series of architectural projects described below: A gradual one and a dialectic one. These building systems were tested in context of extreme sites such as the confluence of rivers, a coastal cliff and an abandoned amusement park. Making the leap from research on modular systems to an architectural design proposal is challenging and certainly not fully developed in the presented papers. Nevertheless the speculation on the architectural qualities of the integrated system was seen as an important part of linking design and research.

7.1. GRADUAL INTEGRATION

As both systems are based upon geometrically similar cells this approach called for defining a spectrum of cells that start of from the initial TI and span to the initial BK by inventing new cells along the way. This resulted in a system with around 6 - 10 Types of different weight, solidity, transparency, material and performance. By doing so this required also to assure valid interfaces between all possibly neighbouring cell types expanding the repertoire beyond the pure TI interface and the BK node connection.

"Performance Fields" started with a TI made from tetrahedra that gradually lost volume through subtractive techniques. The formerly sealed system gains porosity. With a similar gradual approach the development was carried on and transferred to the vector-active skeletal system of BK Figure 5 and 6).

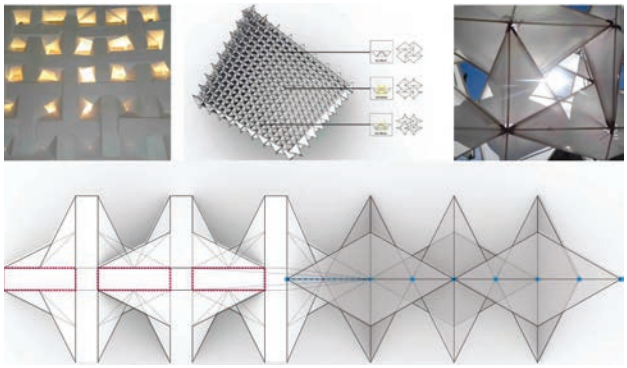

Figure 5. Performance fields by Philipp Mecke. The extreme ends of the modular spectrum are defined by cast plaster modules (top left) and skeletal kite tetrahedra (top right). Mass gradually decreases from left to right (bottom).

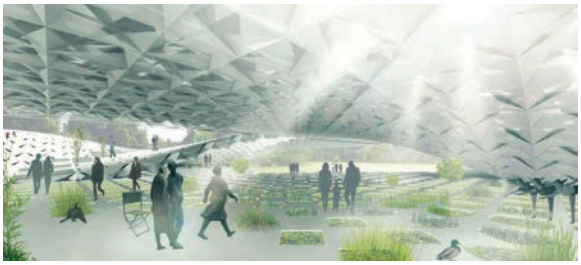

Figure 6. Performance field by Philipp Mecke. Densities, materials and modules types gradually change and adapt to local requirements.

Figure 7. Adaptive Geometric Integration" by Donlaporn Chanachai. Left: The confluence of Rhône and Arve serves as a site for a pier where water, heavily saturated with mineral sediments, meets the clear fluids of the Lac Lemond.

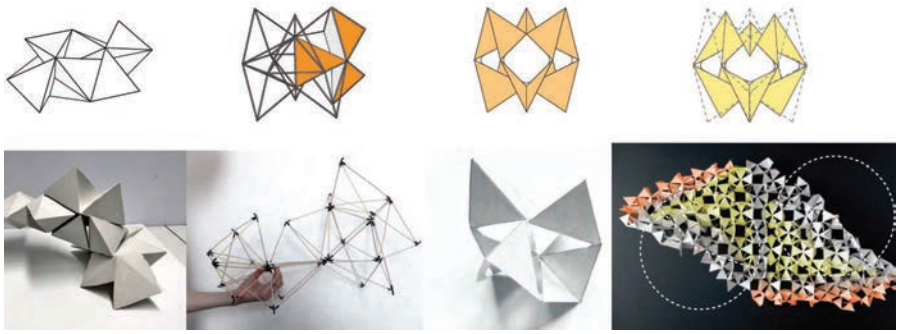

Figure 8. Adaptive Geometric Integration" by Donlaporn Chanachai. Hexagonal modules interlock with two adjacent faces (left). Vector-active and surface-active derivatives are developed for the kite and a lightweight pier structure.

The architectural implementation forms a leisure landscape that seamlessly configures the different module types based on local requirements like flatness for accessibility, cavities for soil hosting or low weight and transparency for large spanning roofs.

Located at the confluence of two rivers in Switzerland the project "Adaptive Geometric Integration" alters and relocates the Bell Kite system from air flow to the fluid flow management while the massive parts provide human access to a formerly inaccessible site (Figure 7). The TI challenges the limitation of interlocking cubes and tetrahedrons by inventing a hexagonal module with a more complex thrust-reducing interlocking behaviour (Figure 8).

Further on architectural functions and performances were mapped to different cells in the spectrum such as structural-foundation, counter weight, water container, buoyancy device, planter, structural column, sun-sail, water collector.

7.2. DIALECTIC INTEGRATION

This approach was aimed at maintaining the two systems as clearly as possible but finding ways of creating singular, linear, and spatial interfaces between them (Figure 9). This lead to solutions where a vertical structure of BK elements would join linearly into a vertical spanning structure of TI. In other instances undulating layer of BK was resting in parts on a pile of TI.

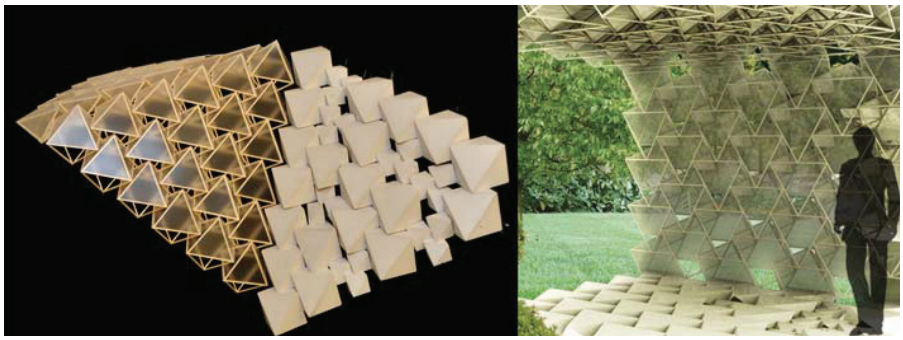

Figure 9. A recursive cube system controls porosity by differentiating element dimension. The lightweight system is clearly distinguished from the TI.

8. Conclusion

This research aimed at synthesising two very different design systems, both coming with their particular dependencies. The TI always requiring a fixed boundary condition, the BK being depended on some anchoring or counter weight. Where the boundary requirement of the TI poses a design problem on how that situation is articulated (Tessmann, 2012), the anchoring of the BK finds a perfect match in the gravity-ruled TI. In that respect the dependency of one system could be solved by the characteristics of the other, integrating them into a single system that performs beyond geometric similarities.

As the architectural community becomes more familiar in designing in systems, this research demonstrates the possibilities and potential of merging systems and thus overcoming inherent limitations while maintaining their internal dependencies.

There is also an interesting subset of further questions on different levels such as tectonics, education, and analysis, which could from the basis of further research in more detailed aspects.

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References

Brocato, M. and Mondardini, L.: 2010, Geometric methods and computational mechanics for the design of stone domes based on Abeille's bond, *in* C. Ceccato; L. Hesselgren; M. Pauly; H. Pottmann; J. Wallner (eds.), *Advances in Architectural Geometry 2010*, Springer-Verlag, Vienna, 149–162.

Estrin, Y., Dyskin, A. V., and Pasternak, E.: 2011, Topological interlocking as a material design concept, *Materials Science & Engineering C-Materials For Biological Applications,* **31**(6), 1189–1194.

Evans, R.: 1995, *The Projective Cast*. Cambridge, MA: MIT Press.

Tessmann, O.: 2012, Interlocking Manifold: Kinematically constrained multi-material systems, *in* L. Hesselgren, S. Sharma, J. Wallner, P. Bompas, J. Raynaud (eds.), *Advances in Architectural Geometry 2012,* Springer-Verlag, Vienna, 269–278.

Wachsmann, K.: 1959, *Wendepunkt im Bauen,* Otto Krauskopf Verlag GmbH.

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A METHOD FOR COMPARING DESIGNERS' BEHAVIOR IN TWO ENVIROMENTS: PARAMETRIC AND GEOMETRIC MODELING

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Abstract. Previous research into designers' behaviour in parametric environments suggests that parametric tools support or promote design processes in a wide variety of ways. However, despite the results of such research, there is a lack of empirical evidence directly comparing how design in parametric environments differs from design in traditional environments. Aiming to address this issue, a pilot study is presented in this paper comparing designers' behaviour in parametric design environments (PDEs) with that in more traditional, geometric modelling environments (GMEs). In the study five designers completed two design tasks respectively in PDEs and GMEs. By employing the method of protocol analysis, different behaviours in the two design environments were identified and compared. This paper focuses on the results of testing the experimental setting and of the coding scheme used in the study. One example set of results from the pilot study is reported – wherein the designer's behaviour exhibits some differences between the two environments – in order to provide an example of the coding used.

Keywords. Parametric design environments; geometry modelling environments; designers' behaviour; protocol analysis; pilot study.

1. Introduction

Applications of parametric design in architecture have become increasingly prevalent in recent years. Woodbury (2010) argues that design processes in parametric design environments (PDEs) are different from those in other design environments due to the unique characteristics of PDEs. For example, by changing the parameters of an object, particular instances can be altered or created from a potentially infinite range of possibilities (Kolarevic, 2003). Previous studies suggest that parametric tools can advance design processes in a variety of ways (Iordanova et al., 2009; Lee et al., 2012; Qian et al., 2007). However, despite this past research, there is a lack of empir-

ical evidence for many of the claims about designers' behaviour in PDEs. The central problem is that there is no basis for comparison. How, for example, can parametric design encourage higher levels of creativity (a common claim) when similarly structured data about creativity in traditional design practice is not available. Thus, the overarching question that drives the present research is, how do PDEs affect or change designers' behaviour in comparison to that in traditional geometry modelling environments (GMEs)? To address this question, this paper described a process for comparing designers' behaviour in PDEs and GMEs. In the pilot version of the study presented hereafter, designers were asked to complete two different design tasks with similar levels of complexity in PDEs and GMEs. This paper focuses on the method used, protocol analysis, and some preliminary results are recorded and discussed.

2. Background

2.1. DIGITAL DESIGN ENVIRONMENTS—PDES AND GMES

Past research has suggested that sketching can assist design thinking as an effective design medium (Black, 1990; Schön, 1983). In a similar way, with the increasing application of digital design tools, scholars have started to study the influence of computational design tools on design processes (Bilda and Demirkan, 2003; Fallman, 2003; Gero and Tang, 1999; Kim and Maher, 2008). Parametric design, in its computational form, is a new way of thinking about architectural design although its impact on designers' processes hasn't been so well explored. In order to undertake such an exploration, two, different design environments need to be identified.

- **Parametric design environments—PDEs.** Parametric design is a dynamic, rule-based process controlled by variations and parameters, in which multiple design solutions can be developed in parallel. The term "parameters" relates to factors which determine a series of variations. In architecture, parameters are usually defined as building controls or environmental factors. Currently, typical parametric design software includes Generative Component (Bentley Corporation), Digital Project (Gehry Technology) and Grasshopper (McNeel). Scripting tools include Processing based on Java language, Rhino script and Python script, based on VB language from McNeel. In the study described in the present paper Grasshopper was chosen as the parametric design environment. Grasshopper is both an advanced environment for facilitating conceptual design and it is relatively widely used in the architectural profession.
- **Geometry modelling—GMEs.** Since the emergence of digital design tools in the design industry architects have found that working with 3D geometry is preferable to working only with 2D (Bilda and Demirkan, 2003; Kan and Gero, 2009). With the development of BIM, 3D geometry modelling software has gradually replaced 2D drafting software and become the main design tool applied in the building environment. Typical 3D geometry modelling tools applied in architecture include

ArchiCAD (Graphisoft), Revit (Autodesk), Rhino (McNeel), Maya, Sketchup, etc. In the study reported in this present paper, we choose Rhino as our geometry modelling environment for the comparison. The reasons are: first, Rhino is advanced in free-form making so it will not lead to significant differences from the product produced in the Grasshopper environment; second, Grasshopper is an add-on in Rhino, which means that the two design environments are on the same platform. This property serves to minimize the variables in the experiment setting.

2.2. FBS ONTOLOGY

How then to classify the behavior of a designer in an environment? Gero's FBS ontology (1990) has been applied in many cognitive studies (Kan and Gero, 2005; Kan and Gero, 2009). Its advocates argue that it is potentially able to capture most of the meaningful design processes (Kan and Gero, 2009) and it provides clear transitions between design instances. In the present study it is introduced as the conceptual foundation for developing the coding scheme for protocol analysis. The FBS ontology (shown in figure 1) contains three classes of variables: Function (F), Behaviour (B) and Structure (S). Function represents design intentions or purposes; behaviour represents how the structure of an artefact achieves its functions; and structure represents the components that make up an artefact and their relationships.

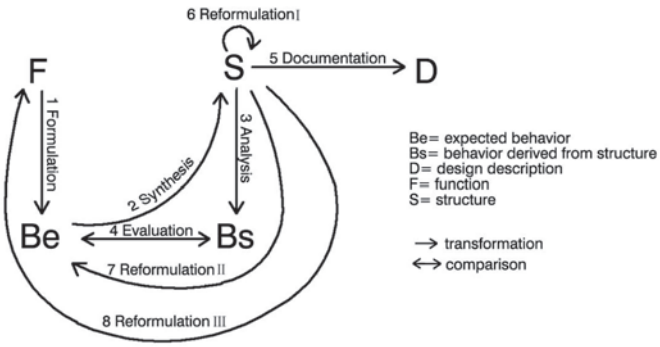

Figure 1. FBS ontology (Gero, 1990).

3. Research Method

3.1. PROTOCOL ANALYSIS

Protocol analysis is a method that is widely used for cognitive studies into designers' behaviour during design processes (Cross et al., 1996; Ericsson and Simon, 1980).

This method has been applied across a variety of design environments (Kan and Gero, 2009; Kim and Maher, 2008). The general procedure for protocol analysis is that the protocol data (in this case, the video-recorded information of designers' interaction with the design environments) is collected from the experiment and then transcribed and segmented. A customized coding scheme is then applied to categorise segments. Through statistical analysis of this data, the character of designers' behaviour can be identified. Protocol analysis deals with a relatively small number of samples, but enables in-depth exploration of designers' cognitive behaviour.

3.2. CODING SCHEME

This study compares designers' cognitive behaviour in PDEs and GMEs using protocol analysis, and as categorized in accordance with the FBS ontology. The categorization or elements – the coding scheme – is described in this section. The key issue in developing an appropriate coding scheme is to capture designers' behaviour as they are working.

The seemingly obvious difference between parametric design and traditional geometry modelling tools is concerned with the application of a rule-based algorithmic process. However, to a certain extent, architectural design has always been a rule-based algorithmic process. Renaissance and Baroque treatises describe logical, rule-based, and parametric methods for creating form and ornament. But as Ostwald (2012) notes, such methods were often peripheral to the design process in the historic examples, while they have become central or pivotal in the most recent developments. For example, in PDEs designers not only design by applying design knowledge, but also by defining and applying rules and their logical relationships using parameters. In GMEs, the rules are present, but less significant or less central. Thus, in this study, discussion of the rule algorithm refers to the generative engine using rule algorithm. For instance, in the design knowledge level of the model, architects use design knowledge to address how the building adapts to the site, how people use the building and how to satisfy the requirements of clients. In the rule algorithm level, designers apply design knowledge through the operations of parametric design tools, such as defining the scripting rules and their logical relationships or choosing the scripting components suitable for a particular purpose.

Taking this into account, a customised coding scheme based on the FBS ontology was developed, where characteristics of parametric design are reflected (Table 1). Two levels of designers' behaviour were coded: from the design knowledge level and the rule algorithm level. In PDEs, both levels of behaviour occur; while in GMEs, only the design knowledge level of behaviour occurs.

Designers' behaviour includes their design intentions and design actions. Intentions inspire design actions, while actions are reflections of design intentions.

Table 1. Coding scheme.

Category	Name	Sub-category	ID	Description
Function (F)	Requirement-New	Design knowledge	F-K-Rn	Reading the design brief for the first time
	Requirement-Old	Design knowledge	F-K-Ro	Revisiting the requirement
	Intention-New	Design knowledge	F-K-In	Initial definition or interpretation of function
Structural Behaviour (Bs)	Intention-New	Design knowledge	Bs-K-In	Behaviour interpreted from structures
		Rule algorithm	Bs-R-In	Behaviour from existing scripts
Expected Behaviour (Be)	Intention-New	Design knowledge	Be-K-In	Expected behaviour from design knowledge
		Rule algorithm	Be-R-In	Expected behaviour form rule making
	Intention-Old	Design knowledge	Be-K-Io	Changing the expected behaviour from design knowledge
		Rule algorithm	Be-R-Io	Changing the expected behaviour from rule making
Structure (S)	Intention-New	Design knowledge	S-K -In	Expected structure, about size, colour or shape
	Intention-Old	Design knowledge	S-K -Io	Changing the structure
	Geometry element making-New	Design knowledge	S-K-Gn	Initial making of the geometry or talking about the modeling method
		Rule algorithm	S-R-Gn	Setting the component for the purpose of making the geometry
	Geometry element change-Old	Design knowledge	S-K-Go	Changing the existing geometry or modelling method
		Rule algorithm	S-R-Go	Changing the component for the purpose of changing the geometry
	Parameter-New	Rule algorithm	S-R-Pn	Setting parameters
	Parameter change-Old	Rule algorithm	S-R-Po	Changing or resetting parameters
	Relationship-New	Rule algorithm	S-R-Rn	Setting the parametric relationship
	Relationship change-Old	Rule algorithm	S-R-Ro	Changing the parametric relationship

They are further divided into “new” and “old” actions. “New” means that a design instance has happened for the first time, while “Old” means a design instance has happened previously. From analysing the transition between “old” and “new” instances, the “changing” action affecting designers’ behaviour is identified.

3.3. EXPERIMENT DESIGN

In devising the experiment for the pilot study, five designers completed two different design tasks with similar levels of complexity in PDEs and GMEs. Participants were all experienced architects who have had at least two years of parametric design experience and an average seven years of experience in architectural design. The experimental environment was a computer installed with Rhino and Grasshopper. During the experiment designers’ activities and their verbalization (of these activities) were video-recorded by a screen capture programme; the recorded data forms the basis of the protocol analysis. There were two design sessions, one session using Rhino (GMEs) and the other session using Rhino and Grasshopper (PDEs). Designers were asked to finish both sessions in 40 minutes for each design session (80 minutes total). Task 1 was a formal massing concept for a community centre and task 2 was a similar concept for a shopping centre. Both buildings contained some specific functional requirements. The design sessions and tasks were randomly matched prior to the experiment. The two design tasks were created to have similar levels of complexity. Through these decisions, the research method has sought to minimize the impact of variables other than the two different design environments.

4. Results

The aim of the pilot study was to test the effectiveness of the experiment setting and the coding scheme as a precursor to undertaking the main study. Therefore, in this paper, the results focus on testing the experiment setting and the coding scheme. The results of one of the five designers from the pilot study are provided as an example coding for comparison of behaviour in the two environments.

4.1. TESTING THE EXPERIMENT SETTING

The designers each showed a clear ability to understand the design brief and operate the software. The time limit meant that now all design outcomes were resolved to the same level. Some designers stopped at the building mass or a façade design. However, they all considered the site planning as well as the building function in more detail providing a considered response to the conceptual design brief. In both PDEs and GMEs, designers started by reading the brief and inspecting the site model provided. During the design process, they also revisited the design brief. The design

brief provided details concerning functional constraints and site conditions. It was up to designers to decide how many of these conditions to consider. As usual in architectural design, different designers have their own design strategies: some designers preferred to start from functional analysis, thinking through site conditions and road and traffic information before, drawing diagrams of the site to explore these relationships. Other designers focused on the geometry modelling as the priority.

In the experiment, designers rarely sketched so that almost all their actions occurred in the computer. That ensured the design environment was within PDEs and GMEs. During their design processes, designers were asked to "think aloud". In the experiment, some designers verbalized their thinking better than others. This is one of the limitations of the "think aloud" method which has been criticized as overtly influencing participants' perceptions (Ericsson and Simon, 1993; Suwa and Tversky, 1997). In our experiment, there was a post-interview about the design session if the designer didn't provide a sufficient level of "thinking aloud" to interpret their actions.

4.2. TESTING THE CODING SCHEME

In the first round of testing the coding scheme captured most of the cognitive design activities in both GMEs and PDEs. For example, in the sample testing, 82.2% of the segments were coded in PDEs, while in GMEs, 84.1% were coded. It was also notable that most of designers' verbalized protocols were accompanied with non-verbalized moves. The two levels (rule algorithm and design knowledge) of design activities have therefore been able to be distinguished clearly.

During the coding process, the categories of "new" and "old" were sometimes ambiguous. In the parametric design process, rules were structured continuously and iteratively meaning it was hard to distinguish whether designers were setting a new rule or making changes to an existing rule. Meanwhile, the categories of geometry making and structure intention became confusing. Most of the time, these appear to happen together, making the coding difficult. Therefore, it was necessary to adjust the details of some subcategorys of the coding scheme.

4.3. A SAMPLE CODING

This is a sample coding from one designer's protocol. The purpose of this is to provide an example to demonstrate some levels of comparison between the two different design environments.

- **Design issue analysis.** In the FBS ontology, the four classes of concept are called design issues. They are function (F), expected behaviour (Be), behaviour derived from structure (Bs), and structure (S). From the analysis, during the parametric design process, the designer considered the brief from both design knowledge and rule algorithm perspectives. As shown in Figure 2, this designer's activities shifted

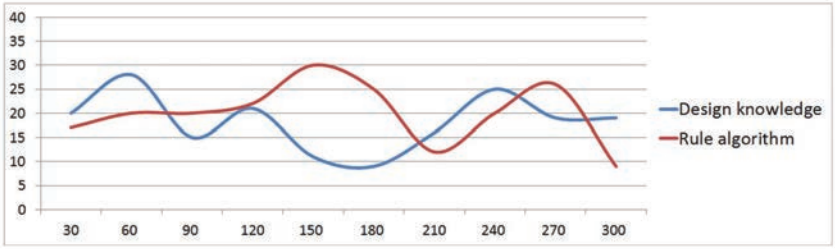

Figure 2. Designer's two levels of activities in PDEs.

between these two levels. At the beginning of the design session, the designer considered more design knowledge than rule algorithm. The possible reason is that at the early design stage, the designer analysed the brief and started to form the design concept based on design knowledge.

As shown in Figures 3 and 4, in both GMEs and PDEs, the designer had the highest amount of structure related activities and the least function related activities. This matches the results of previous cognitive studies using the FBS ontology

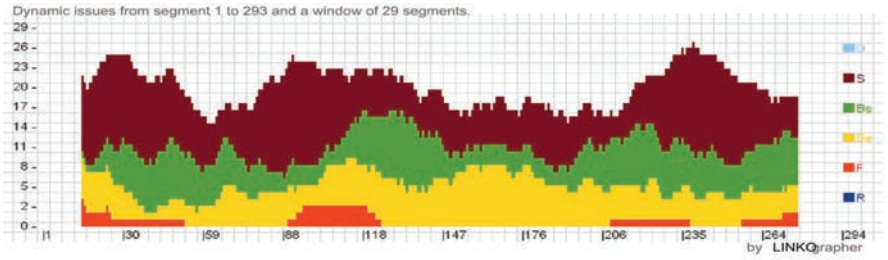

Figure 3. The distribution of "design issues" in PDEs.

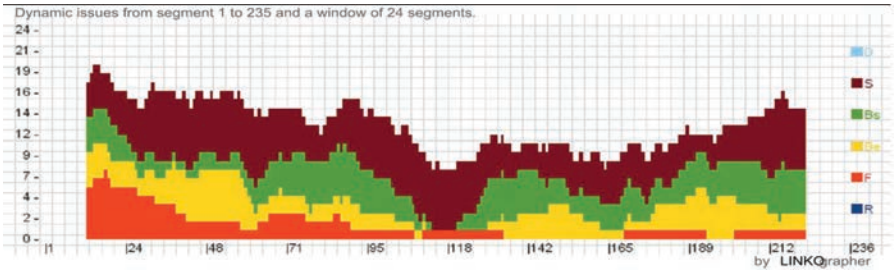

Figure 4. The distribution of "design issues" in GMEs.

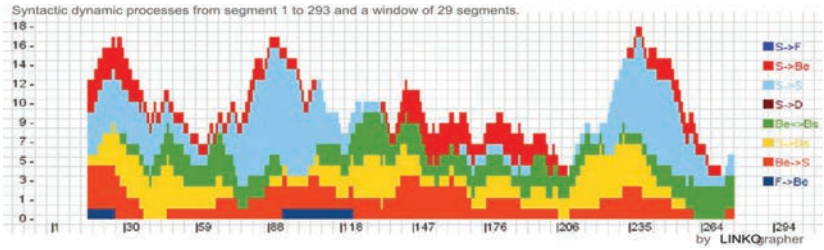

Figure 5. The distribution of "design process" in PDEs.

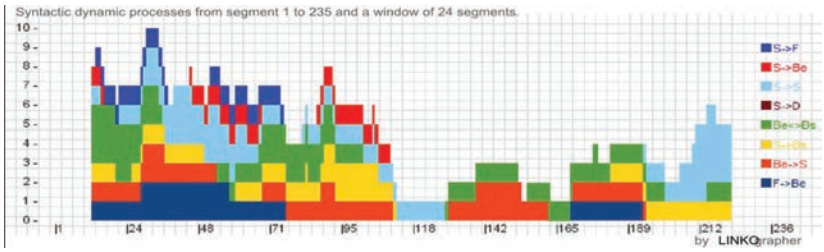

Figure 6. The distribution of "design process" in GMEs.

(Kan and Gero, 2005; Kan and Gero, 2009). In the mid design session, the designer was more active in PDEs than in GMEs. In particular, the Be coding is much higher in the PDE than in the GMEs. This is because the designer set algorithm goals more frequently in the mid design session. Additionally, there are more functions in GMEs than in PDEs. That is probably because in PDEs, the designer concentrated on the rule algorithm design; while in GMEs, the designer had more time to think about the function or requirement of the brief.

- **Design process analysis.** As shown in Figures 5 and 6, there were more meaningful design processes than issues. There are eight design processes (see figure 1) presented in the FBS model. In PDEs, they are distributed consistently throughout the whole design session. There are much more reformulation processes in PDEs, especially reformulation 2, which is the transition from S to Be. This shows that this particular designer, in the PDE, tended to introduce more new variables and directions. More analysis processes occurred in PDEs (from S to Bs), possibly due to the way the designer evaluated the geometric model more frequently.

5. Conclusion

This paper presents an analysis of a sample coding of the results of a pilot study exploring the differences between designers' behaviour in PDEs and in GMEs. The

purpose of the present paper is not to draw conclusions about PDEs or GMEs, but rather to demonstrate that the method is viable. Thus, the pilot study reveals that: 1) the experiment setting is achievable on the practical level and serves the research aim. 2) The sub-category of the coding scheme needs to be revised in order to better capture designers' activities. 3) From the sample coding provided, different design issues and processes can be identified to characterise parametric design. These preliminary results of behavioural patterns identified provide us with a better understanding regarding the impact of parametric design. Furthermore, the pilot study provides a sound foundation for adopting protocol analysis for the future main study.

References

Bilda, Z. and Demirkan, H.: 2003, An insight on designers' sketching activities in traditional versus digital media, *Design Studies*, **24**(1), 27–50.

Black, A.: 1990, Visible Planning on Paper and on Screen, *Behavior and Info. Technology*, **9**(4), 283–296.

Cross, N., Dorst, K. and Christiaans, H.: 1996, *Analysing design activity*, Wiley, New York.

Ericsson, K. A. and Simon, H. A.: 1980, Verbal reports as data, *Psychological Review*, **87**(3), 215–251.

Ericsson, K. A. and Simon, H. A.: 1993, *Protocol analysis: verbal reports as data*, MIT, Cambridge, MA.

Fallman, D.: 2003, Design-oriented human-computer interaction, *Proceedings of the SIGCHI conference on Human factors in computing systems*, Florida, 225–232.

Gero, J.: 1990, Design prototypes: a knowledge representation schema for design, *AI Magazine*, **11**(4): 26–36.

Gero, J. and Tang, H.-H.: 1999, Concurrent and Retrospective Protocols and Computer-Aided Architectural Design, *CAADRIA1999*, Shanghai, 403–410.

Iordanova, I., Tidafi, T., Guité, M., De Paoli, G. and Lachapelle, J.: 2009, Parametric methods of exploration and creativity during architectural design: A Case study in the design studio, *CAADFutures2009*, 423–439.

Kan, J. W. T. and J. S. Gero: 2005, Can Entropy Indicate the Richness of Idea Generation in Team Designing?, *CAADRIA 2005*, New Delhi, India, 451–457.

Kan, J. W. T. and Gero, J. S.: 2009, Using the FBS ontology to capture semantic design information in design protocol studies, *in* J. McDonnell and P. Lloyd (eds.), *About: Designing. Analysing Design Meetings*, CRC Press, 213–229.

Kim, M. J. and Maher, M. L.: 2008, The impact of tangible user interfaces on spatial cognition during collaborative design, *Design Studies*, **29**(3), 222–253.

Kolarevic, B.:2003, *Architecture in the digital age : design and manufacturing*, Spon, New York.

Lee, J. H., Gu, N., Jupp, J. and Sherratt, S.: 2012, Evaluating Creativity in Parametric Design Processes and Products: A Pilot Study, *DCC 2012*, College Station, TX.

Ostwald, M. J.: 2012, Systems and Enablers: Modeling the impact of contemporary computational meth-ods and technologies on the design process, *in* N. Gu and X. Wang, (ed.), *Computational Design Methods and Technologies: Applications in CAD, CAM and CAE Education*, IGI Global, Pennsylvania, 1–17.

Qian, C. Z., Chen, V. Y. and Woodbury, R. F.: 2007, Participant Observation Can Discover Design Patterns in Parametric Modeling, *ACADIA2007*, Halifax, 230–241.

Schön, D. A.: 1983, *The reflective practitioner: how professionals think in action*, Basic Books, New York.

Suwa, M. and Tversky, B.: 1997, What do architects and students perceive in their design sketches? A protocol analysis, *Design Studies*, **18**(4), 385–403.

Woodbury, R.: 2010, *Elements of Parametric Design*, Taylor and Francis.

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EXPLORING DESIGN STRATEGY IN PARAMETRIC DESIGN TO SUPPORT CREATIVITY

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Abstract. This paper deals with the generative and evolutionary aspects of parametric design. We aim to provide a better understanding of individual design strategies to support creativity in parametric design via protocol analysis. An in-depth analysis conceptualises subjects' creative strategies into two models: problem-driven strategy and solution-driven strategy. The solution-driven strategy progress design in the solution space resulted in the highest value in the level of creativity. This is one of potential aspects of parametric design. Exploring design strategies in parametric design contributes to its effective use.

Keywords. Design strategy; parametric design; creativity; protocol analysis.

1. Introduction

Parametric design has become an emerging research issue. It refers to the use of the parameter, which allows for quick searches for alternative solutions (Madkour et al., 2009). Parametric design here focuses on the formative and generative design using 'advanced parametric applications (Holzer et al., 2007)' viz., Grasshopper™, CATIA™ and Generative Components™. The scripting activities (Qian et al., 2007) based on the parameter and rules in parametric design – algorithmic activities (Lee et al., 2012) – allow for different design approaches and variations from conventional design strategies. Nonetheless, our understanding of the generative and algorithmic features of parametric design and the role of creativity is limited.

We have aimed to bridge this knowledge gap. Our previous research (Lee et al., 2011; Lee et al., 2012) has presented both process and product-based evaluation of creativity, while this paper specifically addresses designers' strategies in parametric design.

We hypothesise that the design strategy applied may enhance/hinder creativity in the early conceptual design stage. Designers choose their own strategies in problem-solving processes (Weth, 1999; Ho, 2001; Kruger and Cross, 2006). This is related to an individual design thinking process identified by Analysis-Synthesis-Evaluation (Jones, 1992; Mc Neill et al., 1998). This paper applies the above thinking process to interpret the designer's problem/solution driven strategies. An understanding of the design strategy's relationship to parametric design, not yet understood, but is considered critical for its effective use.

To explore the design strategy applied by an individual during design thinking, this research utilises protocol studies (Suwa et al., 1998; Mc Neill et al., 1998), to develop an understanding of design strategies used in parametric design. This protocol study provides empirical evidence to support the understanding of individuals' design strategies, as they relate to creativity in parametric design.

This paper is divided into four parts. Section 2 explores the related literature and then presents a framework for exploring design strategies in parametric design. A protocol study investigating three designers' strategies is presented in Section 3. Finally, Section 4 concludes with a discussion and outlines the directions for future work.

2. Related Research

2.1. DESIGN STRATEGY

Creativity is a natural component of design process (Hasirci and Demirkan, 2007). Kim and Kang (2003) developed five creative-related tests: a personal creativity mode test, a brain bias test, Torrance Test of Creative Thinking (TTCT), a brainstorming test, and a visual reasoning test. Though the application of these tests is capable of identify the personal characteristics and performances of a designer, there is a limitation in exploring individual preference and habit in design problem solving.

Kruger and Cross (2006) argue that design strategies employed by designers are related to both design quality and creativity. Weth (1999) relates that strategies contain information relating to how the final goal is achieved. Design strategies define sub-goals which limit the possible operation. That is, design strategy is closely related to personal preference and habit and largely contributes to defining designs' thinking processes.

Evidence is presented (Weth, 1999; Ho, 2001; Kruger and Cross, 2006) which considers design strategy as the problem-solving process. Ho (2001), through the application of protocol analysis, identified problem decomposition strategy and working-forward/backward strategy can be used to differentiate between expert and novice designers. Ahmed et al. (2003) indicate that experts use particular

design strategies, whilst novices tend to use trial and error as their design method (backward reasoning). Kruger and Cross (2006) support the concept of a problem or solution driven design strategy. Their findings identified that the use of a solution driven strategy produces lower solution quality but higher creativity. A problem driven design strategy results in the best balance between quality and creativity. These studies identify the relationship that the design strategy has on design quality, efficiency and creativity.

2.2. RESEARCH FRAMEWORK

For the purpose of better understanding an individual's design strategies, protocol analysis (Mc Neill et al., 1998; Ho, 2001; Kruger and Cross, 2006) was utilised. In protocol analysis, a coding scheme is essential and should be devised specifically for the purpose and the design environment. The coding scheme developed in our previous studies (Lee et al., 2012) was enhanced for the purpose of better exploring design strategies. There is considerable literature reporting on research that adopts 'Analysis–Synthesis–Evaluation' as a design method (Jones, 1992). Mc Neill et al. (1998), for example, employed this method as the micro strategy coding scheme: analysis of the problem; synthesis of a candidate solution, evaluation of a candidate solution, and other activities. The study, reported here, based its coding scheme on this model. Our coding scheme consists of three categories: analysis, synthesis, and evaluation.

'Analysis' decomposes a problem into sub problems (Jones, 1992; Ho, 2001). The coding scheme in Table 1 enables us to identify introducing new ideas (SF-Initial Goal), new geometric ideas (SF-Geometry SubGoal), and new algorithmic ideas extended from a previous idea (SF-Algorithm SubGoal). These cognitive activities belong to the conceptual level of Suwa's work (Suwa et al., 1998).

'*Synthesis'* refers to the re-composition of sub problems in different ways (Jones, 1992; Ho, 2001). We deal with two sub-levels which differentiate between 'physical' and 'conceptual'. The distinction between the two sub-levels allows for capturing the generative aspect of parametric design, which is different from common synthesis of a solution. Adopting an idea also belongs to the conceptual level of *'Synthesis'*. This enabled us to distinguish physical depiction from conceptual synthesis which better supports creativity in parametric design.

'*Evaluation'* refers to the test of the performance of new structures (Jones, 1992; Ho, 2001). One code (SE-Geometry) – evaluating primitives or existing geometries – identifies the geometric cognitive activity. Two codes in the algorithm level reveal the algorithmic activities, which are related to evaluating existing parameters and rules as specific activities in parametric design. The algorithm level may refer to evaluating the problem (Purcell et al., 1996), which

Table 1. Coding scheme for design strategy in parametric design.

Category	Code	Description	Sub-code
Analysis	An_p	Introduce new ideas (or goals) based on a given design brief	SF-Initial Goal
		Introduce new geometric ideas extended from a previous idea	SF-Geometry SubGoal
		Introduce new algorithmic ideas extended from a previous idea	SF-Algorithm SubGoal
Synthesis (Physical level)	Sy_p	Create directly geometries	RG-Geometry
		Change existing geometries	RG-Change
		Create initial parameters	RA-Parameter
		Change existing parameters	RA-Change Parameter
		Create initial rules	RA-Rule
		Change existing rules	RA-ChangeRule
Synthesis (Conceptual level)	Sy_c	Make generation (or variation)	R-Generation
		Adopt new ideas to geometries	SA-Geometry
		Adopt new ideas to parameters	SA-Parameter
		Adopt new ideas to rules	SA-Rule
Evaluation (Geometry level)	Ev_g	Evaluate primitives or existing geometries	SE-Geometry
Evaluation (Algorithm level)	Ev_a	Evaluate existing parameters	SE-Parameter
		Evaluate existing rules	SE-Rule

belongs to *'Analysis'*. That is, the algorithm level can be regarded as the activities of evaluating both a problem and a solution space of parametric designing.

Our previous research (Lee et al., 2012), evaluating creativity in parametric design, was based on a two-pronged approach: a protocol analysis procedure (process-based evaluation), and a selective criteria-based assessment method (product-based evaluation). This paper reveals that designers' parametric design strategy is a component of our overall framework, which enables us to investigate three perspectives of creativity in parametric design: person (interpreted as individual design strategies in our study), process and products.

The hypothesis of the overall framework is that the sequence of coded segments will (i) identify cognitive patterns that reveal insights into creativity in parametric designing; these findings will (ii) relate to the results of expert panel assessments evaluating the design outcomes; so as to then derive relationships between these results with (iii) the designer's strategy and/or preference. This paper focuses on the third stage of the framework.

3. A Protocol Study

To collect protocol data, participants were given one hour to undertake a given design task using parametric modelling tools of their choice, whilst adopting think-aloud protocols, the design sessions were video-recorded. The study involved three participants (a lecturer and two postgraduate students). The brief, presented verbally to by the researcher, concerned the conceptual design of a high-rise building as an ill-defined design problem.

The protocols of each recorded video were directly transcribed using NVivo 9 software and automatically segmented into smaller episodes. The average value of the number of segments was 263.5 (Session 1: 142, Session 2: 286, Session 3: 368). Over 90% of each protocol was encoded using our adopted coding scheme, regardless of the use of the parametric design environments (Grasshopper, Maya Script Editor, and Python). This implies that our coding scheme enables the effective encoding of the protocol data.

3.1. OVERALL FINDINGS

Table 2 shows the results of the coding process which describes the percentage of the frequency weighted by time span (calculated by time duration of each code). This allowed us to determine the time devoted to each component of the design strategy as well as main levels of individual design thinking of each participant. On average the coverage of *'Synthesis'* accounts for 53.7%, *'Evaluation'* accounts for 30.2%, and *'Analysis'* accounts for 9.6%, which is the smallest component.

The representation activities of S2 are highest, while 'analysis' of S2 is relatively low. This participant, a postgraduate student, had a tendency to solve the problem by first goal search. This may indicate the procedure of novice's problem-solving. Literature (Ho, 2001; Coley et al., 2007) indicates that a novice designer may lack problem analysis or scoping skills or strategies. S2 also struggled with

Table 2. The percentage of coding result of each protocol.

Category	S1	S2	S3	Mean	SD
Analysis	17.5	4.2	7.0	9.6	7.0
Synthesis (Physical level)	45.0	56.2	38.6	46.6	8.9
Synthesis (Conceptual level)	4.3	3.4	13.5	7.1	5.6
Evaluation (Geometry level)	18.6	8.7	16.2	14.5	5.2
Evaluation (Algorithm level)	11.2	17.0	19.0	15.7	4.1
Sum	96.6	89.5	94.5	93.5	3.6

trial and error (novice's backward reasoning by Ahmed et al. (2003)). By contrast, the 'analysis' identified that S1 achieved the highest mean value of 'synthesis (physical level)'. This Subject, considered an expert (lecturer) in parametric modelling tools, applied strategic rules from the initial states of the problem, which is called the working-forward search strategy (Ho, 2001).

One interesting outcome relating to S3's performance was that both 'synthesis (conceptual level)' and 'evaluation (algorithm level)' – evaluating the problem (Purcell et al., 1996) – were very high. These approaches may have advantages for evolving and generating creative design variations, because these are related to both the co-evolution process of the problem and solution spaces (Dorst and Cross, 2001; Maher, 2010). S3's design also received the highest score from the judges in our product-based evaluation (Lee et al., 2012). That is, design strategy weighting of both the problem and solution spaces plays a significant role in creativity in parametric design.

3.2. DESIGN STRATEGY IN PARAMETRIC DESIGN

The encoded data was visualised to facilitate the exploration of design strategies over time. Figure 1 illustrates the five levels of design thinking – Ev_a: Evaluation (algorithm level), Ev_g: Evaluation (geometry level), Sy_c: Synthesis (conceptual level), Sy_p: Synthesis (physical level), and An: Analysis – in sequence and to compare the changes over time.

While Sy_p and Ev_g can be seen to be dominant activities over time, occurrences of both the An and Sy_c codes differ more significantly between all three

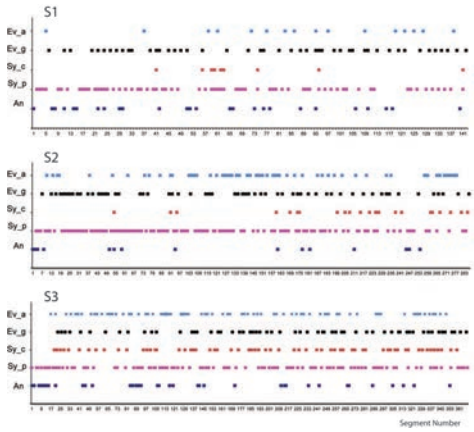

Figure 1. Patterns of design thinking (Ev_a: Evaluation (Algorithm), Ev_g: Evaluation (Geometry), Sy_c: Synthesis (Conceptual), Sy_p: Synthesis (Physical), and An: Analysis).

designers. The Sy_c – synthesis (conceptual level) – within the protocol of S3 occurred at regular intervals throughout the time period. The analysis also happened regularly in the protocols of S1 and S3. The problem space in our coding scheme is based on 'analysis', whilst the solution space highlights 'synthesis (conceptual level). That is, S3 used design strategy highlighting both the problem and the solution. These features of the S3's design strategy, which are consistent with the results of Table 1, may enhance creativity in parametric design.

The An and Sy_c codes did not happen regularly in the protocol of S2, which may be the feature of the novice's problem-solving in parametric design. The Sy_c (conceptual level) appeared towards the end of the protocol. He repeated the procedure highlighting the representation (Sy_p) and the evaluation of algorithms (Ev_a). These features may have disadvantages in creativity. S1 showed the regular occurrences of 'analysis' but a small number of activities encoded by making generation (Sy_c). The problem space is based on 'analysis', while the solution space weights the generative aspects of parametric design.These features imply that he adopted a problem-driven strategy rather than a solution-driven strategy to produce his design product.

Figure 2 shows the occurrences of three cognitive activities of 'analysis' over time. It enables the investigation of problem decomposition strategies in detail. 'SF-Initial Goal' refers to explicitly introducing main problem, while two codes introducing sub goals deal with sub problems.

A closer examination of Figure 2 it reveals that only S1 produces 'SF-Initial Goal' at the beginning, middle and end of the protocol. S1 also sequentially decomposed the problem into geometric sub problems and then algorithmic sub problems. This is similar to 'the explicit problem-decomposing strategy' (Ho, 2001). Figure 1 also supports that S1 adopted a problem-driven strategy. Kruger and Cross (2006) argued that a problem driven design strategy produces the good

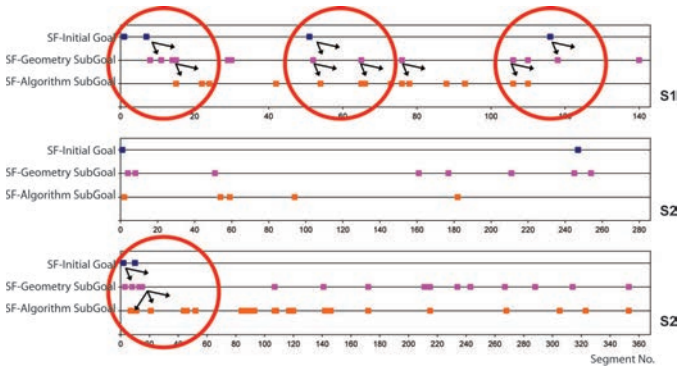

Figure 2. Three cognitive activities of 'analysis' over time.

results of both overall solution quality and creativity. Our observation and product-based evaluation consistently show that the level of usefulness of S1's model has an equivalent score of S3's model. S2's is the lowest, and S1's and S3's values are similarly higher in novelty and complexity. That is, both the problem-decomposing strategy and the problem-driven strategy may enhance creativity in parametric design. Based on these results, this paper illustrates the conceptual procedures of a problem-driven strategy model in Figure 3.

Figure 2 shows that S2 and S3 tend to use an implicit problem-decomposing strategy, which is often used by novices. S2 produces 'SF-Initial Goal' at the beginning and end of the protocol but rarely sub problems. This implies that he performs unsystematically and adopts the working backward search strategy. By contrast, S3 was keen to decompose the problem into geometric and algorithmic sub problems. Figure 1 reveals that S3 regularly used the conceptual level of synthesis (Sy_c). S3 used design strategy highlighting both the problem and the solution, but his sub problems implicitly followed the generating solutions in Figure 1 (see also sequential sub problems in Figure 2). These features imply that S3 adopted a solution-driven strategy to produce his final design product.

As a result, this paper presents two models enhancing creativity in parametric design: problem-driven strategy and solution-driven strategy in Figure 3. The solution-driven strategy is specific to parametric design. S3's design (using solution-driven strategy) received the highest score from the judges in the level of creativity. This is consistent with the Kruger and Cross's results (2006) that a solution-driven strategy produced higher creativity scores. The strategy also is related to iterative design activities providing the restructuring of components (Verstijnen et al., 1998) and the regulation of elements into comprehensive solutions (Akin and Moustapha, 2004).

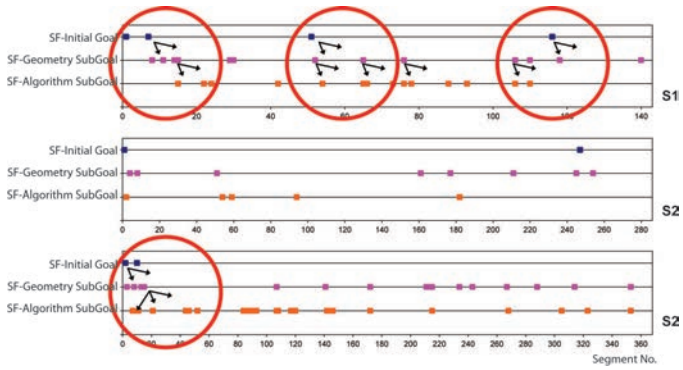

Figure 3. Two models of parametric design strategies to support creativity.

4. Discussion and Conclusion

This paper reports on the exploration of the subjects' design strategies in parametric designing based on the three design levels: 'Analysis', 'Synthesis', and 'Evaluation'. The study presents a formal framework for evaluating creativity in parametric design in terms of the personal aspects of creativity.

The results indicate that the coding scheme used allows for the effective descriptions of design strategies that problem and solution co-evolve. Considering the rating results of the design product in the previous research, these results imply that 'analysis' and 'synthesis (conceptual level)' may support creativity in parametric designing. The authors also summarised subjects' creative strategies into two models: problem-driven strategy and solution-driven strategy. Even though S3 had the features of both novices' and experts' behaviour, his solution-driven strategy making generation in the solution space resulted in the highest value in the level of creativity. This is one of potentials of parametric design.

In summary, this study presents results which provide a better understanding of individual design strategies. As a pilot study, whilst the authors acknowledge the small sample size, the results indicate some unique characteristics of design strategies to support creativity in parametric design. As a starting point, this study provides the potential of exploring design strategies in parametric design.

We continue to investigate other aspects of parametric design. One is the designers' algorithmic preferences. Subsequent research is needed which involves further analysis of algorithms, so called scripting or coding. Scripting activities are a means of representing ideas as well as a channel for creativity (Salim and Burry, 2010). The scripting activities will be categorised into the following algorithmic functions: (Qian et al., 2007): branching, incremental variation, filtering, goal seeking, and mapping and sampling.

Our coding scheme for design strategy in parametric design limits its exploration to exploring the other aspects of cognitive strategies. It needs the second coding scheme such as level of abstraction (Ho, 2001) and expertise model (Kruger and Cross, 2006). This will allow for further investigation and verification of the two models of parametric design strategies to support creativity. Future works also include an in-depth analysis for the purpose of identifying/evaluating the other cognitive design strategies.

References

Ahmed, S., Wallace, K. M. and Blessing, L. M.: 2003, Understanding the differences between how novice and experienced designers approach design tasks, *Research in Engineering Design*, **14**(1), 1.

Akin, O. and Moustapha, H.: 2004, Strategic use of representation in architectural massing, *Design Studies*, 25(1), 31–50.

Coley, F., Houseman, O. and Roy, R.: 2007, An introduction to capturing and understanding the cognitive behaviour of design engineers, *Journal of Engineering Design*, **18**(4), 311–325.

Dorst, K. and Cross, N.: 2001, Creativity in the design process: co-evolution of problem-solution, *Design Studies*, **22**(5), 425–437.

Hasirci, D. and Demirkan, H.: 2007, Understanding the effects of cognition in creative decision making: A creativity model for enhancing the design studio process, *Creativity Research Journal*, **19**(2-3), 259–271.

Ho, C.-H.: 2001, Some phenomena of problem decomposition strategy for design thinking: differences between novices and experts, *Design Studies*, **22**(1), 27–45.

Holzer, D., Hough, R. and Burry, M.: 2007, Parametric Design and Structural Optimisation for Early Design Exploration, *International Journal of Architectural Computing*, **5**(4), 625–643.

Jones, J. C.: 1992, *Design methods*, 2nd ed., Van Nostrand Reinhold, New York.

Kim, Y. S. and Kang, B. G.: 2003, Personal Characteristics and Design-Related Performances in a Creative Engineering Design Course, *Proceedings of the 6th Asian Design Conference*, Tsukuba, Japan.

Kruger, C. and Cross, N.: 2006, Solution driven versus problem driven design: strategies and outcomes, *Design Studies*, **27**(5), 527–548.

Lee, J. H., Gu, N., Jupp, J. and Sherratt, S.: 2012, Evaluating Creativity in Parametric Design Processes and Products: A Pilot Study, *Design Computing and Cognition (DCC'12)*, College Station, TX.

Lee, J. H., Gu, N. and Sherratt, S.: 2011, Developing a framework for evaluating creativity in parametric design, *45th ANZAScA*, Sydney, Australia, Abstracts Book, 17.

Maher, M. L.: 2010, Evaluating Creativity in Humans, Computers, and Collectively Intelligent Systems, *DESIRE'10: Creativity and Innovation in Design*, Aarhus, Denmark, 22–28.

Madkour, Y., Neumann, O. and Erhan, H.: 2009, Programmatic Formation: Practical Applications of Parametric Design, *International Journal of Architectural Computing*, **7**(4), 587–604.

Mc Neill, T., Gero, J. S. and Warren, J.: 1998, Understanding Conceptual Electronic Design Using Protocol Analysis, *Research in Engineering Design – Theory, Applications, and Concurrent Engineering*, **10**(3), 129–140.

Qian, C. Z., Chen, V. Y. and Woodbury, R. F.: 2007, Participant Observation can Discover Design Patterns in Parametric Modeling, *ACADIA 2007: Expanding Bodies*, Halifax, Canada, 230–241.

Salim, F. and Burry, J.: 2010, Software Openness: Evaluating Parameters of Parametric Modeling Tools to Support Creativity and Multidisciplinary Design Integration, *in* D. Taniar, O. Gervasi, B. Murgante, E. Pardede and B. Apduhan (eds.), *Computational Science and Its Applications – ICCSA 2010*, Springer Berlin / Heidelberg, 483–497.

Suwa, M., Purcell, T., and Gero, J. 1998. Macroscopic analysis of design processes based on a scheme for coding designers' cognitive actions, *Design Studies*, **19**(4), 455–483.

Verstijnen, I. M., van Leeuwen, C., Goldschmidt, G., Hamel, R. and Hennessey, J. M.: 1998, Sketching and creative discovery, *Design Studies*, **19**(4), 519–546.

Weth, R. v. d.: 1999, Design instinct? the development of individual strategies, *Design Studies*, **20**(5), 453–463.

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DECODES

A platform-independent computational geometry environment

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Abstract. This paper presents three strategies – host-independence, domain-specificity, and context-appropriate abstraction – for the design of a textual programming environment supporting computational architectural design that more effectively addresses the needs implied by common practices within this community. A survey of existing computational design environments is first presented through the lens of these three strategies. An outline is then presented for a platform-independent computational geometry library built upon each of these strategies, alongside a report of progress made on implementing this platform thus far. More information on this project may be found at http://decod.es/

Keywords. Computational geometry; programming environment; scripting; interoperability.

1. Introduction

In order to design a better programming environment for the architectural design community, it is prudent to first pose a few fundamental questions. What are the computational design environments currently employed in this community? Which ones are useful? Which present obstacles to the needs of common architectural situations?

Architectural design is not dominated by a single unified software platform, and, in stark contrast to other parts of the AEC industry, is characterized by a diversity of competing models, formats, and descriptions of the built environment.

This diversity not only reflects the architectural designers' predilection for moving between a variety of media and software platforms, but also of the naturally collaborative position of the architect who must regularly coordinate across disciplines and among scales. A host of geometric and algorithmic constructs have indeed been created to support these needs, some tailored to specific domains of practice – e.g. recursive tiling definitions and particle-spring systems – while others are more generalizable – e.g. NURBS surfaces and subdivision meshes.

To effectively support the full diversity of representations and operations required by architectural design practice, a computational design environment must meet the following, often competing, requirements:

- Provide access to a rich set of *primitive elements*: domain-specific geometric and algorithmic constructs that make up the world that defines the design.
- Provide appropriate *code structures*: conventions and built-in abstraction methods that allow the user to easily manipulate, modify and extend the set of primitive elements.

1.1. PRIMITIVE ELEMENTS

Most computational designers regularly employ scripts that operate within a host CAD environment, and rely upon the primitive elements offered by this environment. Access to the set of primitive objects and commands within CAD environments is provided via an application programming interface (API). Examples are AutoCAD's "object model" and Rhino's "OpenNURBS" and "RhinoCommon". Most APIs provide access to an interchangeable set of basic primitives such as points, vectors, lines, and meshes, as well as a more specialized set of complex geometric entities like surfaces, solids, or procedurally-based geometry such as subdivision surfaces. More sophisticated CAD environments may address non-geometric primitives, including relationships and constraints governing the parametric definition of geometry, and analytical routines that provide numeric analysis.

The advantages of scripting within such a host environment is demonstrated by the diversity of designs possible through this approach. There are, however, associated costs that may be easily overlooked. For example, there are significant barriers to modifying routines or developing new primitives when adopting an existing CAD library. Primitive elements in such libraries are often bloated with extraneous features and complexity. In RhinoCommon, for instance, there are 13 distinct constructs (RhinoCommon Software Development Kit, 2013) for describing a point object, each one deployed only in particular situations. In addition, more specialized constructs are usually less generalizable, which increases a user's reliance on a specific host environment (Leitão et al., 2012) and reduces the flexibility to operate between multiple host environments and deploy a diverse set of descriptions of the built environment.

Only a small minority of computational design activity takes place outside of an existing CAD environment. By necessity, designs operating independently of an existing CAD library must define the primitive elements from which design iterations are assembled from relatively low-level elements. For example, Kilian and Ochsendorf (2005) have constructed a sophisticated particle-spring system for structural form-finding based only on a rudimentary physics solver. It should be noted that in cases such as this, the libraries developed are intended for a targeted purpose, and are not applicable to computational design problems at large.

1.2. CODE STRUCTURES

All programming environments, whether textual or visual, present a set of code structures that facilitate the manipulation, combination, and modification of their set of primitive elements. Computational design in architecture is carried out by scripting using a variety of programming languages. Thus, it is useful to compare the code structures that make up these languages and the level of domain-specific functionality and abstraction mechanisms that these structures allow.

For textual languages, a number of foundational concepts in the general categories of object representation and manipulation (ex: variables), control flow (ex: logic gates, loops), and code organization and modularization (ex: functions, modules, classes) are needed before one can start creating or manipulating primitive elements. Generally, textual languages have a low level of domain specific functionality in contrast to the high level provided by many visual programming languages. For example, in the Grasshopper visual environment, structures such as m-d sliders, range components, built-in mapping functions for collections of objects, and "wires" that allow for the visual control of data – all provide access to complex geometric constructs in a way that resonates with visual designers, without detailed knowledge of the inner workings of the software. Since the textual languages widely used for computational design today – e.g. Rhinoscript, AutoLISP, and MEL – were developed before visual programming environments gained prominence, they typically make poor companions for visual programming (Celani, 2012). They neither integrate well with their visual counterparts nor do they leverage the advantages of textual programming (Leitão et al., 2012) – such as the robust abstraction mechanisms that facilitate the effective handling of complex problems and the ability to define bespoke routines and geometric descriptions that are applicable across software platforms.

2. A Design-Centred Computational Geometry Environment

A critical reconsideration of what constitutes an effective computational design environment ultimately requires a proper understanding of the target user base.

Members of the computational design community are typically seasoned users of CAD software, and possess an intermediate to advanced level of understanding of computational geometry. However, lacking any direct experience in software development, they typically have a low to novice level of familiarity with algorithmic design. It is our assertion that this tension between a deep understanding of geometry and a shallow understanding of algorithm creates a limitation in the capabilities of our target audience, one that may be mitigated by the proper computational design environment.

This approach is sympathetic with other programming environments designed for this purpose. Autodesk's DesignScript, for example, replaces certain general-purpose functionality with features specific to the demands of a particular domain of use. In this environment, users are permitted to interchangeably pass both lists and singletons into certain methods for the creation of geometry. This feature, while not supported by most general-purpose programming languages and considered questionable practice by expert programmers, is championed by the authors of DesignScript (Aish, 2012) who argue that such features would be considered desirable by the target user base accustomed to an associative CAD-like approach to collections of objects. In what follows, we describe Decodes, a computational geometry environment in development that is built upon three principles that the authors consider critical for the specific needs of the target user base of the architectural design community.

2.1. HOST-INDEPENDENCE

Computational design in architecture requires the ability to work between diverse and often incongruous descriptions of the built environment. The negotiation of these incongruous models is typically handled within scripts that interoperate across software platforms. To more effectively support design, a computational environment should provide mechanisms for easily operating within and between a range of host environments, as well as the ability to act independently of any host environment. The authors seek to develop a computational design environment that better addresses the need for host-independence through the following tactics:

- **Building up from Scratch:** a tabula rasa approach that involves developing a set of primitive elements independent of any CAD environment, sidesteps the associated unpleasantries of working with the complexities of a full-featured CAD environment. The result is a stand-alone environment that is lightweight and focused on foundational concepts to computational design.
- **Broadening the User Base:** this environment is written in a non-compiled scripting language able to be interpreted on the most widely used operating systems (windows, OSX, Unix) in architectural practice, thus encouraging an active use culture that transcends the boundaries between software platforms and operating systems.

- **Interoperating:** a set of routines for translating geometry in and out of a selected set of CAD software facilitates integration into the native scripting environments in such a way that it effectively replaces host-native scripting.

The approach outlined above requires the creation of a core set of geometric objects and operations able to be translated into each member of a set of supported CAD platforms and operating systems. A cross-platform capable scripting language is needed for this purpose. Python was chosen as a base language for the Decodes library, due to its cross-platform capability, its current level of integration with existing CAD platforms, and the availability of abstraction structures appropriate to a computational design audience (as further elaborated in sections below).

To this end, a set of protocols must be developed and maintained for translating between each supported CAD environment or file type and core Decodes geometry. Every construct or property that does not easily translate into existing CAD software requires a decision as to how it will be interpreted. For example, meshes are very generalizable geometric descriptions that are supported by most CAD platforms, but the details of their implementation may vary slightly. In OBJ file formats, meshes may contain either triangular or quadrilateral faces, while certain routines in the Decodes library rely upon exclusively triangular faces. While mesh triangulation represents a relatively trivial translation, more complex geometric descriptions (such as subdivision surfaces and NURBS descriptions of solid-bodies) will require more elaborate translation protocols, or may not be supported at all. Naturally, there already exists many rich, host-dependent geometry libraries; we take advantage of these by wrapping features in these libraries that are well implemented and in-line with the values of our approach.

Protocols for translating from a CAD environment to Decodes are packaged and termed “innies”. Some innies allow for a limited set of user interactive geometry selection or parameter definition. Protocols for translating from Decodes to external environments are called “outies”. Outies allow for the definition of a limited range of geometric object properties, such as layer, colour, object name, etc. At the time of writing, innies and outies have been developed and are functioning at a basic level for a number of packages, while others are planned but not yet fully implemented. Table 1 describes the current state of development for a number of innies and outies. Context-free outies are also possible, either through a “window” (via OpenGL) or an output file (via DXF, OBJ, or SVG), allowing designs to be developed by operating purely within the Decodes library.

Figure 1, below, depicts the same script run in three distinct CAD environments (AutoCAD, Rhino, and Grasshopper) on two different operating systems (OSX and Windows 7). The script was run without modification, and is dependent only on a pre-defined environment variable that defines the scripting context.

Table 1. Translation protocol state of development (current at the time of writing).

Platform	Innie Implementation	Outie Implementation
Rhino (McNeel)	Initial	Full
Grasshopper (McNeel)	Full	Full
AutoCAD (Autodesk)	None	Partial
Sketchup (Google)	None	Partial
Maya (Autodesk)	None	Initial
SVG	N/A	Partial
OpenGL	N/A	Initial

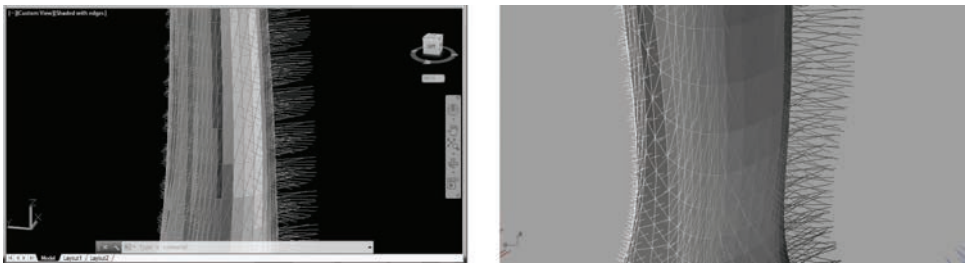

Figure 1. Results of a script, written in Decodes, that calculates the average yearly solar incident radiation across a user-defined mesh, as manifest in AutoCAD and Rhino.

Applying these tactics, the resulting environment is one in which scripts can be reused and easily shared across platforms through simple copy-paste operations. The anticipated impact of this feature is a user base that is expanded to include existing users of all of these platforms, and the creation of broader communities of like-minded users centred on specific computational design approaches rather than on CAD platforms.

2.2. DOMAIN-SPECIFICITY

Computational design depends upon a host of geometric and algorithmic constructs. Some, such as NURBS surfaces and subdivision meshes, are generalizable to other modes of practice and other disciplines, and are typically implemented well in existing CAD platforms. Such constructs are versatile and extensible, but also non-specific and do not themselves directly support high-level computational design procedures. Other constructs, such as recursive tiling definitions and particle-spring systems, are more idiosyncratic to specific domains of practice or to specific design approaches. Such constructs are very useful for the particular task

for which they were developed, but are often difficult for the end-user to modify. An effective computational geometry environment must balance two competing demands:

- **Richness** – access to a large set of commonly used domain-specific geometric and algorithmic constructs, implemented in a robust and flexible manner.
- **Extensibility** – the ease of understanding, modifying and extending this set to accommodate domain-specific tasks not supported by core functionality.

These competing needs are satisfied using the following tactics:

- **Remain Transparent:** the library is implemented within an end-user-accessible scripting language, removing the need for an API. This lowers the barrier for users to contribute extensions and modifications to the core functionality. An active user-base contributing extended libraries can override the natural limitations of a simple, less fully-featured library.
- **Invent Here, Find Elsewhere:** a stand-alone geometric library is developed with functionality specific to the computational design community. Three levels of extensibility are envisioned: a "core" set of basic primitives and functions applicable across CAD platforms, a "contributed" set of extension libraries that provide primitives and functions aimed at a more specific or idiosyncratic task, a set of "hooks" for taking advantage of primitives and functions already implemented in existing CAD platforms.

An approach based on these tactics requires the development of a geometric modelling kernel with functionality specific to the computational design community. Developing this "lean" geometry library from scratch offers the opportunity to reconsider conventional approaches to the core set of primitive objects and operations commonly implemented in CAD software (such as points, vectors, rays, meshes and surfaces), as well as to consider higher-level geometric types that might make beneficial additions to this core set.

The Decodes kernel accommodates the needs of the computational design community through two mechanisms. The primary mechanism is the natural extensibility of Decodes and the anticipated user community actively contributing extensions. As highly valuable extensions are developed and refined, they may be integrated into the core library. The secondary mechanism is the framework of the core library itself, which was developed through an examination of use-cases specific to architectural design. A concurrent thread of research examines situations commonly encountered in architectural design, and has identified seven broad categories of computational strategies that encapsulate tactics that are commonly employed in practice. These are: Aggregation and Tiling, Design Space Exploration, Geometric Decomposition, Agent-Based Forms, Optimization / Satisficing, Modelling for Production and Fabrication, and Interoperating.

Figure 2. Results of a Decodes script that produces a set of Danzer tiles, and employs transformations through the definition of point bases.

This survey of common practices and methods forms the basis of the selection of core methods and features available in Decodes. At the time of writing, the following core geometric classes have been identified and developed to a basic functioning state: Vector, Point, Line, Ray, Line Segment, Mesh, Polygon, Polyline, Curve, Surface, Coordinate System, Transformation, Intersection. Considerations have been made for the multiple design paths that may be taken to similar solutions. For example, Figure 2, below, depicts the results of one of two built-in tiling definition – a 2d pinwheel tiling definition and a 3d Danzer tiling definition – each enacted using a similar means of structuring transformations. Either of these tiling systems may be defined in multiple ways (via Transformations, Coordinate Systems, or by manipulating the underlying Basis of point collections), conforming to the preferred framework brought to the problem by the user.

The result is a transparent, end-user-extensible, geometry library that better addresses the specific needs of the computational design domain. As this is being built from scratch, the geometry kernel currently trades domain-specificity and transparency for complexity and efficiency. On-going development and adoption by an active user base will naturally lead to an ever-richer library of geometric operations and more efficient implementations.

2.3. CONTEXT-APPROPRIATE ABSTRACTION

Designers as a group have been shown to benefit from a particular combination of abstraction mechanisms in their scripting and programming languages. A computational geometry environment for the design community should provide both access to geometric constructs at a lower-level than often found in CAD software, and access to code structures at a higher-level than often found in programming languages and older styles of scripting languages. The authors seek to develop a

computational design environment that offers a more appropriate level of abstraction for a design audience through the following tactics:

- **Providing Low-level Access to Primitive Geometry:** Following the principle of domain-specificity, a set of primitive geometric objects and operations have been developed that target approaches specific to design computation.
- **Exploiting High-Level Features of Modern Scripting:** Modern high-level scripting languages contain a host of features useful for designers without formal training in computer science, including list comprehension, dynamic typing, and support for multiple programming paradigms.

The approach outlined above is primarily manifest in the choice of base scripting languages used for Decodes, but also has ramifications for the coding style employed in development and the abstraction mechanisms that are available to the end user. Python was chosen as a base language due to its cross-platform capability and for the high-level features it offers such as list comprehension, dynamic typing, and support for multiple programming paradigms. Of these, support for dynamic typing has had the most impact in the development of the Decodes library.

A programming language is considered to be dynamically typed if type-checking is performed at run time rather than at compile-time. Under this model, variables are not typed but values are. Dynamically typed languages, such as Python, Ruby, Lisp, JavaScript, VB Script, and Lua, are often used in generative design applications. The popularity of this model may be due to the large number of novice programmers in the generative design community, and the perception that typed variables is a difficult concept for new users to apprehend. While dynamic typing is itself a context-appropriate feature for a design audience, as it removes an often-confounding obstacle to code development, it is the coding style that dynamic typing engenders that has enabled the most innovative feature of the Decodes library. “Duck typing” is a widely employed style of programming using a dynamically typed language. To conform to this coding style, a programmer should be less concerned with an object’s inheritance from a particular class or interface (what an object “is”) than the properties and methods available to that object at any given time (what an object “does”).

Applying a duck typing style to the development of the Decodes allows for the “flexible basis” abstraction mechanism. Point objects in architectural design applications are implicitly defined in Cartesian geometry – relative to an ortho-normal coordinate system in R3. Many computational design environments support a limited set of alternative definitions, including cylindrical coordinate systems, as well as points defined relative to parameterized objects such as curves and surfaces. We may understand a point object to be defined relative to any of these bases, where

the X,Y, and Z parameters of any given point are evaluated by its basis to produce a "world" point in R3. Using a static-typed language, only objects that explicitly announce themselves as deriving from a "basis" super class or interface may perform in this manner, implicitly limiting the set of objects which can act as the basis of a point. A duck typing programming style removes this limitation, allowing any user-defined object to act as a basis.

A "flexible basis" for points is a useful abstraction mechanism for the computational design context, as it allows for the implicit encapsulation of transformations and aggregation structures. A panelization study has been developed that demonstrates the use of a custom basis to define panel placement along a surface. In this situation the custom basis offsets the need for a surface definition, and provides the user with a more precise and reliable means of control when compared to NURBS surface definitions.

References

Aish, R.: 2012. DesignScript: Origins, Explanation, Illustration, *Computational Design Modelling. Design Modelling Symposium*, Berlin 2011, Berlin: Springer, 1–8.

Celani, G. and Vaz, C.E.V.: 2012, Programming Languages For Generative Design: A Comparative Study, *International Journal of Architectural Computing*, **10**(1), 121–138.

Kilian, A. and Ochsendorf, J.: 2005, Particle-spring Systems for Structural Form Finding, *Journal of the International Association for Shell and Spatial Structures*, **46**(2).

Leitão, A., Santos, L., and Lopes, J.: 2012, Programming Languages For Generative Design: A Comparative Study, *International Journal of Architectural Computing*, **10**(1), 139–162.

Pentilla, H.: 2003, Architectural-IT and Educational Curriculums – A European Overview, *International Journal of Architectural Computing*, **1**(1), 102–111.

"RhinoCommon Software Development Kit": 2013. Available from: <http://4.rhino3d.com/5/rhinocommon/> (Accessed February 17, 2013).

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A SCHEMA FOR CAPTURING AND COMPARING PARAMETRIC SPATIAL DATA

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Abstract. In this paper, the authors consider the problem of architectural spatial performance indicators for assessing computer generated design, where identification and analysis of meaningful and relevant spatial qualities is the target of assessment. The paper presents a parametric spatial analysis schema and spatial database structure for the restricted, but still significant, domain of residential housing. A process for the capture and comparison of different types of architectural spatial data is described where analysis focuses on a series of 2D metric and topological spatial measures. The process is then demonstrated in our discussion of a descriptive scenario.

Keywords. Parametric design; precedent, spatial analysis.

1. Introduction

In this paper, the authors consider the problem of architectural spatial qualities and their potential as spatial performance indicators for assessing and comparing computer generated design. The identification and analysis of meaningful and relevant spatial qualities is the target of investigation.

A variety of research efforts over the past decade has seen the development of numerous conceptual design evaluation methods for architectural design, highlighting an opportunity for parametric design software to be used for performance-driven design. However the work to date has been focused on structural, material and environmental criteria (Littlefield, 2008; Toth et al., 2011; Holzer, 2010; Janssen, 2004). Further, whilst attempts have been made to quantify spatial qualities using theories and techniques associated with space syntax (Hillier and Hillier, 1984), the development and evaluation of spatial qualities have been limited in parametric and scripted conceptual design.

The paper presents a framework for architectural spatial analysis, using a parametric-based schema, for the restricted, but still significant, domain of residential housing. The framework presents a process for the structuring, capture and compar-

ison of different types of architectural spatial data where analysis focuses on a series of geometric and topological spatial data extracted from the 3D building model. The paper's focus is limited to the presentation of the framework and schema for architectural spatial analysis, including the method of data extraction and computation of metrics describing spatial qualities – and is therefore a precursor to spatial performance assessment and optimisation. The framework is demonstrated in a simple descriptive scenario focusing on a residential building design and assessment of spatial information using the associative parametric software Grasshopper.

2. Background

> "The task of organization today requires a more explicit and more elaborate repertoire of organizational patterns and more explicit, precise criteria for their evaluation than what can be reasonable expected from the tacit knowledge and accumulated wisdom of an experienced architect" (Schumacher 2012).

Schumacher highlights the increasing complexity of organizational patterns expected in contemporary design and the difficulty in problem solving organizational layouts without decision support. The key theories that can enhance organizational intelligence include set theory and network theory which have been tailored for architecture under the theory and practice of space syntax (Hillier 1984). Computational implementations of space syntax have been constructed but are typically used for the analysis of urban networks; some examples include Batty (2004), Turner (2007) and Jiang et al. (2000).

The most comprehensive use of space syntax for the analysis of residential design is Hanson (2003). Hanson's study compares a variety of London houses through a series of visual comparison techniques including justified graphs grouped by network size and configuration type, shaded integration distribution overlaid onto floor plans, tabulated quantitative data and isovist rays (representations of the visual field at any given point in space). This study demonstrates the possibility of comparing the organisational logic of residential homes.

Methods for capturing spatial topological metadata of apartment layouts for information retrieval have been proposed (Hwang and Choi, 2003, Jeong; and Ban, 2003). These studies demonstrate a capacity to code spatial networks into databases for querying. This study extends this work by introducing parametric software for capturing and comparing the spatial data. The introduction of parametric software allows relational geometry to be constructed (Woodbury, 2010), with this research proposing an advanced toolset for encoding and querying spatial data. Section 3 describes a framework for architectural spatial analysis that incorporates the use of parametric techniques whilst Section 4 will briefly outline the benefits and opportunities available of utilising such a framework.

3. A Framework for Architectural Spatial Analysis

This section describes the proposed framework for architectural spatial analysis, through parametric design techniques. The framework describes a methodology to capture the metric and topological properties of residential buildings and spaces. There are three components to the framework which are: (1) the construction of a structured CAD drawing, (2) a parametric schema for spatial analysis, and (3) data storage through a structured MySQL database. These components are shown in Figure 1.

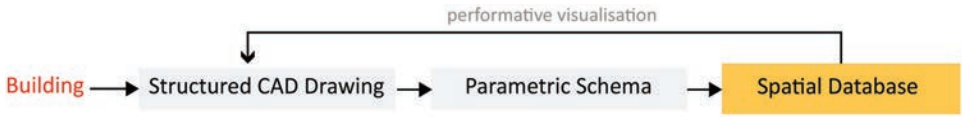


Figure 1. Framework for Architectural Spatial Analysis.

3.1. STRUCTURED 2D CAD REPRESENTATION

The schema relies on the construction or extraction (from a 3D model) of a structured 2D CAD representation, consisting of room outlines represented by polylines that are allocated to CAD layers according to room type. A master set of layers is pre-defined including bedroom, bathroom, living etc. The allocation of rooms onto functional layers allows the parametric schema to extract data. A typical structured CAD drawing is shown in Figure 2.

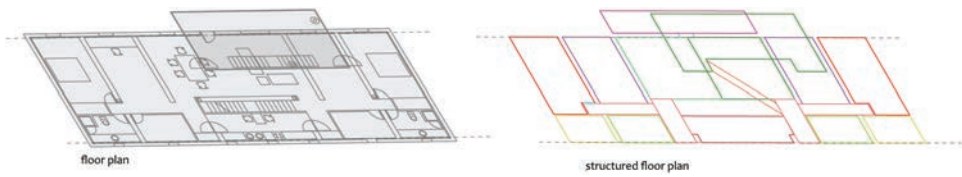


Figure 2. Structured Floor Plan.

3.2. A SCHEMA FOR PARAMETRIC SPATIAL ANALYSIS

Once the structured 2D representation is complete, the parametric spatial analysis schema is applied to extract the spatial data into a specific format that allows the potential for spatial performance analysis. There are three data components of the

proposed parametric analysis schema, namely: (1) room data, (2) configuration data and (3) representation data.

The schema operates across metric, topological and geometric data and implements parametric systems to encode spaces as relational objects. The extent of captured data in combination with parametric systems allow for an extended set of spatial comparisons / queries compared to typical spatial databases, which are typically implemented for GIS data. Some of these possibilities will be discussed in Section 4. The following sections will describe the three types of data that define the schema.

3.2.1. Room Data

The room data collected is based on geometric and topological information that describe each individual room. Figure 3 shows the nine room metrics that are extracted. These include; centre point, room area, perimeter, number of vertices, bounding box area, room to bounding box ratio, length, width and proportion.

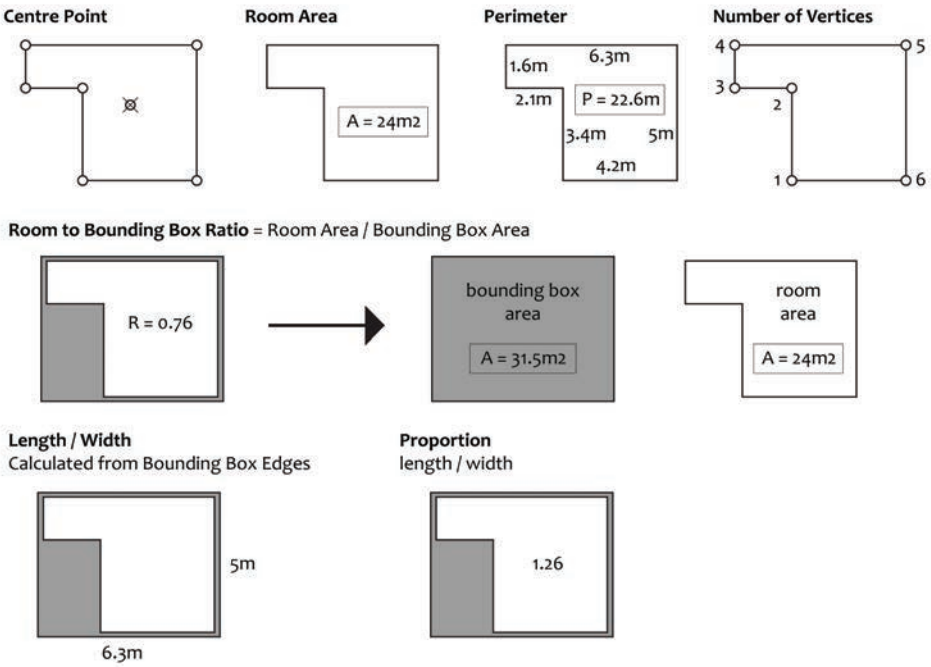


Figure 3. Room Metrics.

The parametric schema captures the spatial data in a structured format suitable for database storage. Each room is constructed as an object through object oriented programming techniques, with each room object containing the spatial metrics as properties. These properties are then encoded into a MySQL database which is described in Section 3.3.

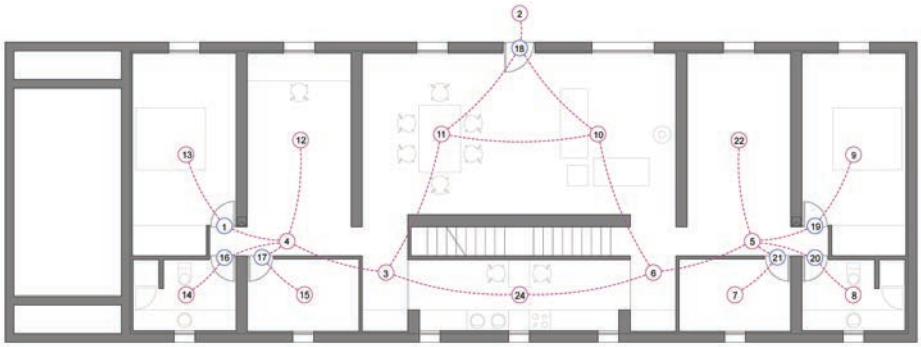
The key benefits of using parametric tools to capture the spatial data include ease of data capture, and the potential for integrated spatial performance comparison through the same environment. Once the metrics have been defined parametrically, the user is able to reference different geometry (i.e. another floor plan) where calculations are then extracted automatically. Since the structured floor plan is constructed parametrically, comparable floor plans from the database can be easily recreated and visualised for comparison within the same parametric environment.

3.2.2. Configuration Data

The next set of data that is extracted is the topological data. This is extracted using a series of methods including visual and textual scripting in the associative parametric software Grasshopper. We use the plugin 'SpiderWeb' developed by Richard Schaffranek to incorporate graph functions, in particular, the 'Graph from Cells' method to convert the structured floor plan into graph data. This operation treats each room as a node and assesses each shape boundary polygon for contact. If the polygons touch, it places a link between the two rooms. This produces an 'all connection' graph which treats all polygons as spaces (including doors) (Figure 4). This is a misleading data set as doors and openings are treated as spaces and can distort the space syntax spatial depth measurement by suggesting rooms are deeper in the network than they actually are.

To calculate more suitable results that reflect the spatial network, scripting techniques are utilized to reconfigure the 'all connection' graph. To begin, the graph is reconstructed taking into account doors. The script bypasses doors and connects the two rooms directly. The link is assigned the associated meta data describing it as a "door" link. Spaces that are not connected through doors are allocated an "open" link. Once the doors are removed from the spatial graph, the graph must be renumbered and cleaned to form a 'minimal graph'.

With the minimal graph, a series of space syntax measurements can be extracted including integration, control and spatial depth (Hillier and Hanson, 1984). Additional spatial data can be collected using isovist rays. Typically isovist fields are assessed visually (Hanson 2003), however the parametric schema collects metric data about the isovists for each space and stores it (with spatial association) in the database. This provides information about the visual permeability of each space



c_id	s_id_a	s_id_b	type
1	4	13	door
2	3	24	open
3	3	11	open
4	3	4	open
5	4	12	open
6	5	22	open

c_id	s_id_a	s_id_b	type
7	5	6	open
8	6	10	open
9	6	24	open
10	10	11	open
11	4	14	door
12	15	4	door

c_id	s_id_a	s_id_b	type
13	10	2	door
14	2	11	door
15	9	5	door
16	8	5	door
17	5	7	door

Figure 4. All Connection Graph.

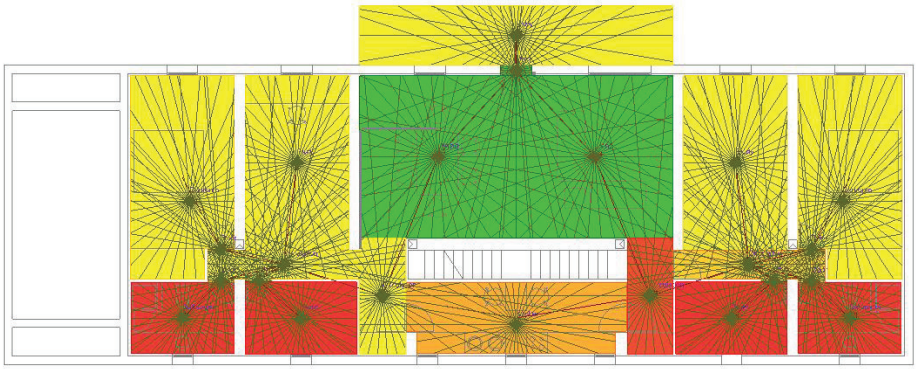


Figure 5. Visibility Isovist Analysis.

in the context of the network of spaces. A number of metrics can be extracted from the isovist rays including the average isovist length, the maxium isovist length and an indicative view direction by connecting a vector from the isovist origin to the centre of the isovist polygon (Figure 5).

The schema capitalises on the relational capacity of parametric software to extend the isovist analysis. The isovist rays extend until they are obstructed by an obstacle, which in this case would be another space. Since the geometry is parametrically constructed, it is possible to determine and record which spaces the isovists are obstructed by.

Typically the computational implementation of space syntax techniques rely on finite analysis grids for calculation (Turner 2001) and hence are more akin to a raster approach of analysis. The parametric relationships reflect a vector approach to data capture, allowing the dynamic mapping of spatial data onto room objects.

3.2.3. Representation Data

The last set of data to be extracted is the representational data. In order to search and compare buildings and spaces, the structured floor plans must be in a format that can be reconstructed to allow re-represenation. To do this, a vector is drawn from the centre of each space to the vertices of each spatial shape outline. This allows any space to be reconstructed parametrically using a point as the base geometry. In addition to the room vertex vectors, additional vectors are captured from the centre of the overall building bounding box to each vertex so that the whole building can be reconstructed parametrically from a single point.

3.3. DATA EXPORT TO STRUCTURED MYSQL DATABASE

A major component of capturing and comparing spatial data is the ability to store the data in a structured format that is searchable. A MySQL database has initially been selected due to the ability to read and write to a database through the parametric software and the ability to access the database through the internet.

The database must take into account the hierarchy of the building. Data must be captured at the level of a building, its spatial network and individual spaces. To accomplish this, a spatial database is constructed so as to contain the following:

- **Building** provides historical information about the building.
- **RoomType** is the lexicon of functional rooms.
- **Rooms** provides a list of actual rooms and room types per building with spatial measurements based on geometric data for each room.
- **Building_Analysis** provides simple and calculated spatial measurements for the building including summations of room measurements.
- **Configuration** describes each spatial link and the type of link.
- **RepresentationBuilding** and **RepresentationRoom** describe each room as a relative vector from the centroid of the building bounding box and room outline respectively.

Table 1. Spatial Database Schema

Table Name	Fields (metrics)	#
Building	B_ID, Name, Location, Year, Architect, Material, Typology	7
Building_Analysis	MeanDepth, MeanRA, MeanRRA, Area, Length, Width, Height, ShapeRatio, BBoxRatio, noFunctionSpaces, noTransitions, area FunctionSpaces, area Transitions, SpaceTransitionRatio	14
RoomType	RT_ID, R_Type, Name	3
Rooms	R_ID, B_ID, R_Type, NoVertices, Area, Perimeter, Length, Width, RL, ShapeRatio, BBoxRatio, RA, RRA, Control, EntryTopologicalDepth, EntryMetricDepth, AvgIsovistMetricDepth, MaxIsovistMetricDepth, AvgIsovistTopologicalDepth, MaxIsovist TopologicalDepth, AvgIsovistDirection	22
Configuration	C_ID, R_ID_A, R_ID_B, Distance, Type	5
RepresentationBuilding	V_ID, B_ ID, vX, vY, vZ	5
RepresentationRoom	V_ID, R_ ID, vX, vY, vZ	5
GlobalRoomAnalysis	R_Type, minNoVertices, maxNoVertices, avgNoVertices, minArea, maxArea, avgArea, minLength, maxLength, avgLength, minWidth, maxWidth,avgWidth, minShapeRatio, maxShapeRatio, avgShapeRatio, minBBoxRatio, maxBBoxRatio, avgBBoxRatio, minRA, maxRA, avgRA, minRRA, maxRRA, avgRRA, minControl, maxControl, avgControl, minETD, maxETD, avgETD, minEMD, maxEMD, avgEMD, minITD, maxITD, avgITD, minIMD, maxIMD, avgIMD	39

- **GlobalRoomAnalysis** a summary table that calculates averages and minimum and maximum measurements across the database. Table is updated when database is updated and allows parametric software to compare designs against whole database upper and lower limits.

Within these separate classes of information there are 100 different metrics. Therefore the structure of the database (see Table 1) has to be carefully considered to allow the storage of this complex data, which includes different geometry types which can be singular or multiple (i.e. a series of vertices consisting of x, y and z coordinates that constructing a room outline).

4. Discussion

In developing the schema, the authors hope to contribute to an understanding of performance measurement in architectural design, showing how precedent-based

spatial data can be captured and compared, and once a complete design corpus is analyzed, how ranges of spatial qualities can be identified and used in a performance-driven generative design process. The processing power afforded by the schema for the capture and comparison of different types of architectural spatial data, specifically derived for use in generative design, is demonstrated here in this simple descriptive scenario.

A structured 2D CAD representation is constructed for a chosen design, which will be called *Design X* in this scenario. Using the schema described in Section 3.2, metric and topological properties are extracted from the representation of *Design X*. Since the database has a corpus of existing precedents, a variety of spatial property ranges can be queried using SQL queries.

At an individual room level, basic comparison queries can include the display of all bedrooms in the database. The query can be extended by displaying all bedrooms and those rooms connected two topological spaces deep to any bedrooms. An alternate query type will display results that are within a range of *Design X's* performance. For example, a query to display all buildings that have an average integration value of +/- 10% of *Design X's* average integration value (a space syntax measure for the relative topological depth of each space) can be readily made. Finally, the designer can make shape based queries, such as the comparison of dimensions and articulation of room outlines.

Capturing data at both the level of the individual room and the spatial network allows flexibility in comparison, with the designer having the potential to compare designs for individual room types or a series of connected rooms and evaluate according to existing precedent data.

5. Conclusion

The authors have described a schema for capturing and comparing spatial data using parametric software. The schema involves creating a structured CAD plan, extracting spatial knowledge using existing and developed strategies and storage into a MySQL database for querying. Future research aims to populate the database with a series of contemporary residential precedents and utilize the database for spatial performative design.

Acknowledgements

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References

Batty, M.: 2004, A new theory of space syntax. CASA working paper #75, available at http://www.bartlett.ucl.ac.uk/casa/publications/working-paper-75

Hanson, J.: 2003, *Decoding homes and houses*, ed., Cambridge university press.

Hillier, B. and Hanson, J.: 1984, *The social logic of space*, ed., Cambridge University Press Cambridge.

Holzer, D.: 2009, Sense-making across collaborating disciplines in the early stages of architectural design, PhD Thesis, RMIT University.

Hwang, J.-E. and Choi, J.-W.: 2003, SpaceScope: Spatial Content-based Retrieval of Architectural Floor Plans, *Proc. The 10th International Conference on Computer-Aided Architectural Design Futures (CAADFutures 2003)*, vol., 53–62.

Janssen, P. H. T.: 2005, A design method and computational architecture for generating and evolving building designs, PhD Thesis, The Hong Kong Polytechnic University.

Jiang, B., Claramunt, C. and Klarqvist, B.: 2000, Integration of space syntax into GIS for modelling urban spaces, *International Journal of Applied Earth Observation and Geoinformation*, **2**(3), 161–171.

Jeong, S.-K. and Ban, Y.-U.: 2011, Developing a topological information extraction model for space syntax analysis, *Building and Environment*, **46**(12), 2442–2453.

Littlefield, D.: 2008, Space craft: developments in architectural computing, ed., RIBA.

Schumacher, P.: 2012, *The Autopoiesis of Architecture: A New Framework for Architecture (Vol. 2)*, ed., Wiley, Chichester.

Turner, A.: 2007, From axial to road-centre lines: a new representation for space syntax and a new model of route choice for transport network analysis, *Environment and Planning B: Planning and Design*, **34**(3), 539–555.

Turner, A.: 2001, Depthmap: a program to perform visibility graph analysis, *Proceedings of the 3rd International Symposium on Space Syntax*, vol., 31.31–31.12.

Woodbury, R.: 2010, *Elements of parametric design*, ed., Routledge, London ; New York.

Toth, B., Salim, F., Burry, J., Frazer, J., Drogemuller, R. and Burry, M.: 2011, Energy-Oriented Design Tools for Collaboration in the Cloud, *International Journal of Architectural Computing*, **9**(4), 339–360.

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PERFORMANCE-BASED PARAMETERIZATION STRATEGIES

A theoretic framework and case studies

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Abstract. In this paper, alternative approaches to structure the parametric geometry in relation to information on various performances are described and exemplified. They relate to different levels of knowledge that concern the performances considered in the process and which are available to the designer while the parametric model is being set. A theoretic framework embeds the different approaches, for which the use of parametric modelling is structured in three phases: strategy-definition; model-building; and solution-assessment. The phases and their interrelations are discussed. Finally, four case studies are presented, focusing on the relation between the knowledge available in strategy-definition and the exploration occurring in solution-assessment.

Keywords. Conceptual design; parametric design; performance analysis.

1. Introduction

In traditional architectural practice, the effort invested to integrate performance measurements in the conceptual design phase is usually very limited. This attitude

is not consistent with the unanimous importance attributed to the conceptual design phase, where the most influential design decisions are taken (Roozenberg, 1993; Chong, 2009). Specifically, exploring different design alternatives is commonly recognized as crucial in conceptual design (Liu et al., 2003; Okudan and Tauhid, 2008; Chong, 2009). While alternatives reveal things to the designer he/she may not have considered, the comparison between alternatives plays a key role in understanding whether a design satisfies certain criteria (Woodbury and Burrow, 2006). However, performance assessments in traditional architectural practice are still limited to a very small number of design alternatives.

Parametric modelling serves the generation of geometric design alternatives and, when coupled with building performance simulation tools, the integration of measurable criteria (Turrin et al., 2011). However, structuring the parametric geometry in relation to information on various performances is crucial. Failing this would mislead the entire process and possibly generate unsuitable outputs. In this paper, we describe and exemplify alternative approaches and present them within a theoretic framework. The different approaches relate to different levels of knowledge that concern the performances considered in the process and which are available to the designer while the parametric model is being set. This paper focusses on the quantifiable performance aspects of design requirements. However, quite a number of requirements are quantifiable, even more when considering that also linguistic architectural choices are mostly translated into the control of physical phenomena.

2. Performance-oriented Parametric Design

According to Barrios (2005), parametric design is the process of designing in a parametric modelling setting. Parametric modelling represents geometric entities having editable attributes, and relationships by means of associations. Attributes can be expressed by independent values, which act as input to the model; their variations generate different solutions of the model. The ensemble of these alternative solutions is named the solution space of the model. The process in which the editable attributes and the associations are set is named the parameterization process; and it usually outputs a hierarchical structure describing a dependency chain. Overall, parametric modelling is a goal oriented process that requires the exploration goal to be properly targeted in advance. The goal oriented nature of parametric modelling is crucial when dealing with performance oriented design.

2.1. THE THREE PHASES OF PARAMETRIC PERFORMANCE ORIENTED DESIGN

Focusing on the conceptual stage of performance oriented design, the use of parametric modelling involves three phases, in which the expertise and knowledge of

the designer is required to meaningfully address the process. During the first phase, strategy-definition, the parameterization process is addressed based on the analysis of design challenges, abstraction of relations between performances and geometry, and formulation of parameterization strategies according to the design intentions and selected performances. During the second phase, model-building, the parametric model is constructed according to the logic that emerges in the first phase. During the third phase, solution-assessment, the design alternatives embedded into the parametric model are explored based on performance evaluations.

The strategy-definition phase depends on the need to define the hierarchical associations based on the explicit representation of a design strategy. A design strategy can be developed through analytical investigation of geometric properties in relation to the design requirements. Once the design requirements are captured and rationalized, the geometric properties that affect their satisfactions can be made explicit. These properties address the focus of the parameterization. While formal frameworks exist for identifying, capturing and managing design requirements (e.g. Hauser and Clausing, 1988) and methods for decomposing requirements (e.g., Lamsweerde, 2001), there is a lack of support for relating requirements to the geometric properties of the design. Design Scenarios (Gane and Haymaker, 2010) offer extensive support in formalizing the process, including the annotation of variable parameters that impact the design requirements. However, the identification of such parameters is left to the multidisciplinary design team and is not specifically addressed in the framework. Nevertheless, the process in which decomposed goals are related to the decomposition of geometric design properties can be formalized in relation to the analysis for performance evaluation.

The formalized process distinguishes four steps. In the first step, given a design concept (here named primary generator according to Darke, 1979) and (quantifiable) design requirements describing the desired performances of the project, preliminary numeric analysis are run on a reference geometry to identify and quantify the level of the eventual missed fulfilments (for example: achievement of thermal or daylight comfort). During this first step, preliminary understanding of challenges and potentials to reach the design goals are identified. In the second step, based on the previous results, the specific sub-goals are established, which decompose the design requirements into more specific tasks (for example: reduction of summer overheating or of light contrast). The output of this second step consists of the list of sub-goals. In the third step, various design aspects are analysed, searching for the ones favouring the achievement of the sub-goals (for example: increasing thermal mass or reduce direct light transmittance). The impact of the design aspects can also be further verified by means of preliminary numeric analysis. The output of this third step consists of the list of properties of the primary generator that impact the achievement of the sub-goals. Finally, in the

fourth step, geometric properties are extracted for the aspects having positive impact on the goals. These geometric properties are the ones to be parametrically investigated; therefore, their attributes are parameterized. The list of these geometric properties and their attributes is the output of the strategy-definition phase. Based on the so established parameterization strategies, the parametric model can be built (model-building phase). Subsequently, the solution-assessment phase concerns the evaluation of different design solutions in search for well performing instances (desired solution space) among the ones embedded in the parametric model (actual solution space). This exploration can involve different methods, mainly according to the breath and meaningfulness of the solution space, both of which depend on the strategy-definition phase. This aspect is discussed below.

2.2. RELATIONS BETWEEN STRATEGY-DEFINITION AND SOLUTION-ASSESSMENT

The three phases of parametric performance oriented design are not linearly dependent, but directly interrelate with each other. The interrelations between the performance-oriented parameterization in the strategy-definition phase and the performance-oriented exploration of the solution space in the solution-assessment phase are particularly important, especially concerning the meaningfulness and the breath of the solution space.

The meaningfulness of the solution space indicates that the instances are expected to express a meaningful range of variations on key aspects affecting the analysed performance. This is needed in order to successfully explore the solution space for identifying well performing solutions. Since different independent parameters and hierarchical associations (in other words, different outputs of the parameterization process) identify different solution spaces, the meaningfulness of the solution space depends on the parameterization and, therefore, on the strategy-definition phase. Also the breath of the solution space depends on this phase, because it is determined by the number and ranges of variable parameters. The breath can be calibrated depending on the knowledge available to the designer during the parameterization process. Sufficient knowledge may prevent the exclusion of meaningful solutions when relations between geometry and performance are uncertain. Additionally, the more knowledge is available during strategy-definition, the more the actual solution space can be made to coincide with the desired design solution space and the need for analyses during solution-assessment can be reduced. As an extreme case, formulating a deterministic relation between the variation of the geometric attributes and the performance trend allows a coincidence between the generated instances of the model and the well performing configurations.

3. Case Studies

In this section, four case studies are discussed, focusing on the relation between the knowledge available in strategy-definition and the exploration occurring in solution-assessment. In the first case study, a process is presented in which only a few relations between geometry and performances were formulated; as a consequence, the parameterization broadened the number and range of parameters, enlarging the solution space of the model. In the second case study, the knowledge available during strategy-definition was also initially limited, but different ways to increase the knowledge in this phase were explored. Specifically, analytical numeric calculations were joined with physical measurements and testing in order to gain knowledge and extract the meaningful geometric parameters, and therefore narrow the solutions space. This process is discussed in terms of an iteration relating the different phases. In the third case study, this process is further developed, until it allows the definition of a deterministic relation between performance and geometry. Finally, in the fourth case study, a deterministic relation is formulated upon previously available knowledge.

3.1. CASE STUDY 1: LARGE SOLUTION SPACES

The first case study presents a process where the identification of well performing solutions relied mainly on the solution-assessment phase, investing far less effort in the strategy-definition phase. It concerns the design of a pavilion by a student (Friedhoff Calvo, 2010). Of the overall design process, only the aspects concerning daylight are presented here. The design requirements specify an interior space uniformly lit by indirect daylight, with the exception of spots of intense direct light creating differentiated areas. The envelope of the pavilion is intended to filter the daylight to create these effects. The primary generator for the envelope took inspiration from Escher's tessellations and was based on interlocking complementary rhomboids. Having defined the primary generator, the student limited the strategy-definition to a preliminary analysis (using Autodesk Ecotect software) to generally determine which variables to consider and which limits to take into consideration. Meaningful relations with daylight were identified concerning the overall shape of the envelope, the density (and therefore dimensions) of the components, the percentage of variable openings – a relation was formulated between the definition of the openings and the position of the sun – and other meaningful aspects were identified in non-geometric properties, such as materials and colours. The parameterization for the model was set according to the geometric aspects to be explored, with the overall shape parameterized in order to achieve different curvatures, the density of the components based on their UV distribution, the relation with the solar vector based

on an angle of tolerance, and the percentage of opening area based on various distances of offsets and heights of extrusions. The parametric model was built (model-building phase) and its solution space explored (solution-assessment phase). In order to search for geometric combinations having light qualities with the desired effects, daylight simulations were made in Radiance for a number of instances. Radiance also allowed the investigations of different material properties on the same geometric solutions. No computational search techniques were coupled with the parametric model and performance evaluation software. In order to guide the search and reduce the number of iterations for evaluations, the evaluation process was subdivided into three steps: the effects on the daylight produced, respectively, by the variation in the curvature of the whole envelope, the material qualities, and the percentage of closed/open areas in the components were tested separately.

Despite the advantages of creating a large set of design alternatives to be analysed numerically, two main levels of difficulties were encountered by the student. The first regards the parameterization process, which was based on intuitive conception and preliminary identification of relations between geometry and daylight effects. The second regards the selection of the instances to be evaluated, which was deemed to be the most challenging aspect, if performed without the use of computational search techniques. The high number of possible instances and the complexity of the geometry made the performance behaviour highly unpredictable to the student. Despite the decomposition of the search process into three separate steps, the options to be evaluated were difficult to choose. The integration of further computational support for the exploration of design alternatives is confirmed as valuable with respect to this difficulty (Turrin et al., 2011). However, the remaining case studies explore a different direction, consisting of increasing the analysis during strategy-definition in order to reduce the number of variables and increase the capacity to predict their influence on performance.

3.2. CASE STUDY 2: NARROWED SOLUTION SPACES

The second case study tackles ways to narrow the solution space by increasing the coincidence between the actual and desired solution spaces. It presents the design of an interchange station by a student for his M.Sc. graduation project (Van Kersbergen, 2011). The part of the work presented here focuses on the design of the envelope for daylight performances. For each function daylight requirements were defined according to the building regulations, the design intentions and preferences between direct or indirect light, the level of acceptance for discomfort given by glare and required safety (for which glare could create risks). The overall configuration of the building was previously defined, based on design requirements highly affected by the large geometry, such as the complex functions

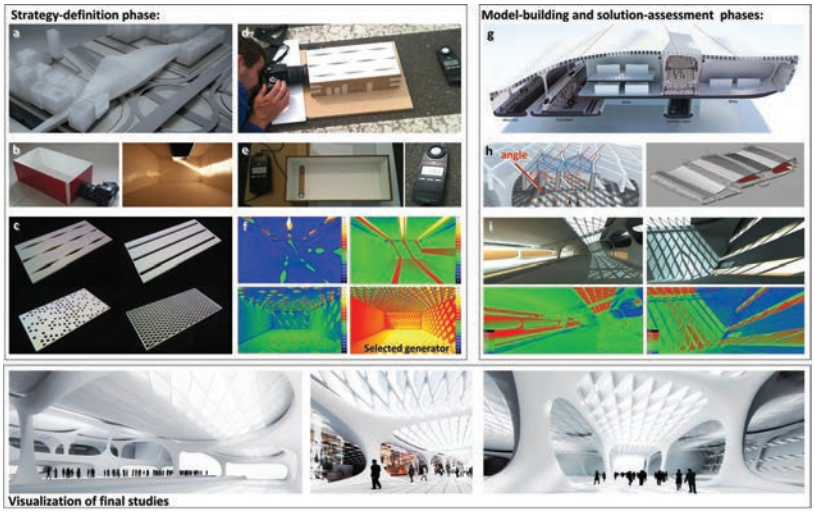

Figure 1. The figure illustrates the overall process. Given the envelope's overall shape (a), preliminary (non numeric) analyses (b) lead to defining four primary generators (c), which are numerically analysed on: physical models with sensors (d,e); digital measurements from camera (f); digital models for simulations. The selected generator is applied (g); the parametric model is built based on the identified meaningful parameters (h); and performance is assessed for a chosen configuration (i). (individual images taken from Van Kersbergen, 2011).

of the infrastructure and the wind-driven airflow. For the design of the envelope, the overall process is illustrated in Figure 1 and described here following.

In contrast to the previous case study, four alternative primary generators were conceived for the envelope during the strategy-definition phase. Within this phase, initially, an early set of preliminary (non numeric) analyses were made on physical models. Based on their results, the four generators were formulated using the geometric properties detected as significant. Subsequently, more preliminary analyses ran transversally across the four primary generators, for each of which both physical and digital tests were made on partial models. The physical tests allowed collecting numeric data used for both a deeper understanding of the factors affecting the daylight performance and calibrating the digital analysis. Digital tests were run on multiple variations of the system. The process allowed selecting one primary generator (consisting of a diamond based grid) and its meaningful geometric factors. For these, two families of geometric parameters were identified, respectively controlling the horizontal and vertical inclination of the cladding elements. Based on the so identified cladding, the overall surface of the envelope was then tessellated. Additionally,

a parameter concerning the material properties (translucency of the panels) was identified as relevant for investigation. The parametric model was built (model-building), and its solution space explored (solution-assessment) based on performance evaluations that were run for the different areas of the project, according to the different functions and daylight requirements. The geometric configuration and the materials chosen by the student to run the first analyses were assessed as relevantly close to satisfactory for the desired performance. For further investigation and possible improvement, tests on slightly adjusted parameters were recommended.

This case study shows the potentials of performing deep analyses in the preliminary phase of the process. They allowed the identification of meaningful geometric factors; they also allowed understanding and drawing a relation between the variation of the geometric factors and the performance trend. In this way, the geometric configuration set as first solution to be analysed has emerged already close to the desired performances.

3.3. CASE STUDIES 3 AND 4: DETERMINISTIC SOLUTION SPACES

The previous case study has shown how relevant a deep preliminary analysis phase is in order to meaningfully narrow the parametric solutions space to be further explored. The remaining case studies exemplify this attitude brought to its extreme consequences. In these cases, parametric modelling was used to explore a set of geometric variations only after the relation between the changes in geometry and performance trend was fully understood and mathematically expressed. As a result, the solution space does not contain alternative design solutions to be explored searching for well performing configurations; instead they represent one or more design configurations satisfying the analysed design requirements.

The third case study focuses on acoustic absorption as a design requirement, with the aim of designing an indoor architectural product. The project was developed by a student for her M.Sc. thesis (Setaki, 2012). The primary generator was defined by the student only after the strategy-definition phase was finalized. This consisted of a relevant number of tests, which included conception and 3D-printing production of different prototypes embedding a number of geometric variations to study their impact on sound absorption. Only when clear principles were formulated, the primary generator was conceived and its parameterization process finalized upon the principles extracted during the tests. Guarantee of good performance is expected from the instances of the parametric model. The model acts in this case as generic design tool applicable in future projects, to parametrically generate different design solutions according to different acoustic conditions.

The fourth case study focuses on structural performances of form-active roofs reacting to varying wind load conditions, with the aim of designing a large span

structure for covering a sport field. The project was developed by a student for his M.Sc. thesis (Liem, 2011). After a preliminary exploration of possible adaptive structures, the primary generator was based on a modular grid structure, for whose structural behaviour established theory was available. During strategy-definition, the research focused on methods to find forms based on minimized bending moments and included performance evaluations of preliminary configurations. The identification of meaningful variables could rely on pre-existent theories, which allowed the parameterization to embed clear mathematical formulations. Also in this case, a design tool was developed by the student. A planar grid of points having variable positions (except for the perimetral supports), and directions and intensities of the loads (expressed as independent parameters) can be used as input to the design tool. The distribution of the point grid is calculated based on mathematical formulations and search for solutions to mathematical equations. Through this process, the tool enables determining the geometric configurations of a discrete form-active structure to minimize its bending moments under variable load conditions.

Both case studies exemplify an effective way to limit the parametric design solution space to a set of well performing solutions, to generate both specific configurations suitable for different designs (as in the case of the acoustic absorber) or well performing configurations of adaptive structures (as for the form-active discrete system). This approach presumes a preliminary solid knowledge and understanding of the analysed performances and the possibility to formulate a relation between geometry and performance.

4. Conclusions

The paper presented and discussed the three phases in which parametric performance oriented design can be structured (strategy-definition, model-building, solution-assessment); and tackled the interrelations among these phases, with specific emphasis on the relations between strategy-definition and solution-assessment with respect to meaningfulness and breath of the solution space to be explored. Four case studies were presented. The first case study focuses on large solution spaces; the second on increased performance analysis during strategy-definition in order to increase the correspondence between the actual and desired solution spaces, and therefore narrowing the actual solution space. The other two case studies focus on the full coincidence between the actual and the desired solution space, based on deterministic relations between geometry and performances, formulated either based on knowledge extracted during strategy-definition or on previously established knowledge. In conclusion, the choice the designer makes concerning the time and effort investment during the different

phases and the awareness concerning the consequences of the attitude taken at the different phases of the process are essential. An absolute judgment concerning the right attitude to be taken is here avoided in favour of a choice that needs to be made according to the different design cases. The choice is especially dependent on the level of knowledge and understanding that is possible to be achieved in the strategy-definition phase within a reasonable time for the process. Ideally, a high availability and use of knowledge has to be recommended; and time investment could be particularly convenient when general knowledge useful also for future projects can be gained.

References

Barrios, C.: 2005, Transformations on Parametric Design Models, *Computer Aided Architectural Design Futures 2005*, Springer, Vienna, 393–400.

Chong, Y. T., Chen, C.-H. and Leong, K. F.: 2009, A heuristic-based approach to conceptual design, *Research in Engineering Design*, **20**(2), 97–116.

Darke, J.: 1979, The Primary Generator and the Design Process. *Design Studies*, **1**(1), 36–44.

Hauser, J. and Clausing, D.: 1988, *The House of Quality*, Harvard Business Review, Cambridge, MA.

Friedhoff Calvo, M. A.: 2010, Investigations on a Parametric Double Component Structure and its design opportunities in the field of natural illumination, Report for Design Informatics Study, MSc Course, Delft University of Technology, Delft, the Netherlands.

Lamsweerde, A.: 2001, Goal-Oriented Requirements Engineering: A Guided Tour. *Proceedings of the 5th IEEE International Symposium on Requirements Engineering*, Toronto, 249–263.

Liem, Y. A. B: 2011, Graphic statics in funicular design: calculating force equilibrium through complementary energy, MSc Thesis, Delft University of Technology, Delft, the Netherlands.

Liu, Y.-C., Chakrabarti, A. and Bligh, T.: 2003, Towards an 'ideal' approach for concept generation, *Design Studies*, **24**(4), 341–355.

Okudan, G. E. and Tauhid, S.: 2008, Concept selection methods – a literature review from 1980 to 2008, *Int. Journal of Design Engineering*, **1**(3), 243–277.

Roozenberg, N.: 1993, On the Pattern of Reasoning in Innovative Design, *Design Studies* **14**(1), 4–18.

Setaki, F.: 2012, Acoustics by additive manufacturing, MSc Thesis, Delft University of Technology, Delft, the Netherlands.

Turrin, M., von Buelow, P. and Stouffs, R.: 2011, Design explorations of performance driven geometry in architectural design using parametric modelling and genetic algorithms, *Advanced Engineering Informatics*, **25**(4), 656–675.

Van Kersbergen, D. J.: 2011, Schiphol Interchange Station - Integrated design research for the wind and daylight performance of the building envelope, MSc Thesis, Delft University of Technology, Delft, the Netherlands.

Gane, V. and Haymaker, J.: 2012, Design Scenarios: Enabling transparent parametric design spaces, *Advanced Engineering Informatics* **26**(3), 618–640.

Woodbury, R. F. and Burrow, A. L.: 2006, Whither design space?, *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, **20**(2), 63–82.

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SONIC DOMES

Solving acoustic performance of curved surfaces by interfacing parametric design, structural engineering and acoustic analysis

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Abstract. This paper addresses the acoustic performance of complex curved surface geometries that are commonly known to pose problems of sound concentration, thus affecting speech intelligibility and audience experience in spaces of temporal arts performance. It reviews an open system of design research in which parametric design process, structural analysis and acoustic analysis are deployed to improve the sound of ellipsoidal structures in relation to sound source and audience positions, by adapting the height, dimension and centre point of a dome structure, consequently improving the acoustic behaviour of the performance space. The paper discusses an iterative design, analysis and optimization processes, in which a number of generative form variations were developed in Grasshopper, and reworked in McNeel Rhino, tested in engineering software (Strand7), and evaluated in acoustic simulation (ODEON). This allowed an interdisciplinary team to develop, test and evolve a design proposal that shows one solution for avoiding sound concentration and consequently improving acoustic performance in complex intersecting and curved geometries of a multifunctional building.

Keywords. Parametric design; sound concentration; curved surfaces; structural engineering; acoustic simulation.

1. Introduction of Context: Acoustic Performance of Curved Surfaces

This research investigates the acoustic performance of curved surface geometries by employing variations of parametric models to evaluate spatial, structural and perceptual criteria. Specifically, the quality of spaces for spoken word is dependent on a good understanding of the relationships between geometry and acoustic performance, and their impact on speech intelligibility and soundscape unfolding for the

spectator. Several different options of curved surfaces in relation to circular and circle-intersecting volumes are tested through computational acoustic analysis techniques suitable for the prediction of sound concentration. The research discusses the acoustic properties of complex geometries with curved surfaces, and reviews how the acoustic performance can be modified through geometry manipulations.

Generative design offers a tight control of duration, force flow, structural deformation, material agencies, and spatial behaviour. In complex curved structures, a catenary logic (self-regulation and optimisation of structures in response to internal force flows) may be applied to solve structural requirements. An acoustic optimisation is usually performed at the end of a design process by the introduction of absorbing materials or amplification, instead of geometrical optimisation using acoustic simulation as an integral part of the design process. Yet, specifically in spaces for temporal arts, the acoustic performance of generative and structural variations is critical. (Reinhardt et al., 2012). When parametric design, structural analysis and resulting acoustic simulation are interfaced in analytical cycles, complex curved morphologies can be designed without retreating to secondary sound improvement measures, through reviewing the performative criteria in direct relation to the geometry.

The context of the research is a design with four interlocking domes, which answered structural requirements set by extreme lateral and vertical forces, but posed a challenging acoustic behaviour due to sound concentration resulting from an ellipsoid geometry. Thus, the research employs the creation of a parametric model and structural and acoustic simulation transfers, to enable an improved acoustic performance of curved surface geometries. The paper presents an open agenda between different collaborative realms; the generative digital design as realm of strategic design (3D modelling in McNeel Rhinoceros and scripting in McNeel plugs-ins: Grasshopper); the structural analysis realm as area of construction requirements (Finite Element Analysis in Strand7); and the acoustic analysis as an arena of the immersive experience (simulation in B&K ODEON), in order to provide a platform in which different partners of a collaborative team can interact.

2. Performative Spaces: Reflections, Reverberation, Speech Intelligibility and Simulation

In acoustics, a number of descriptors serve to identify the relationship between materials, architectural configuration and perceived sound characteristics, which aid design for temporal arts spaces (theatre plays, concerts, or dance performances). *Sound Reflection* seldom exists in isolation; sound will almost always find a surface on its path, where a reflection will be created. Understanding how a material reflects sound is an important step in making predictions of the behaviour of sound in a room, as all surfaces reflect and absorb to an extent. *Reverberation Time* is one of the most common acoustic descriptors of a space. Depending on the

absorption coefficient of surfaces, sound will be absorbed and reflected creating a reflection pattern that governs perceptual acoustic characteristics of rooms. *Speech intelligibility* refers to the ability of a listener to understand speech on a given acoustical situation, and is intrinsically related to reflection patterns of sound. Speech intelligibility can be increased by early reflections that increase the level of a speaker in a room. Yet when reflections arrive at a later time, the beneficial effects of reflections reverse as earlier utterances mask later utterances, therefore degrading speech intelligibility. Speech intelligibility may also suffer with unfavourable acoustic conditions such as strong late reflection (echoes) and sound focusing due to specific geometries of a space (Reinhardt et al., 2012). *Acoustic Simulation* enables the critical investigation of an acoustic performance in the design and revision of existing and future spaces. Through acoustic simulation, relationships between source, reflection patterns and acoustic descriptors at a receiving point can be used to determine the quality of acoustic performances.

3. Acoustical Phenomena and Concentration in Complex Curvatures

When sound encounters a surface it can be absorbed, reflected, diffracted or transmitted, and will, depending on the spatial morphology, result in different acoustic responses in terms of sound reflection. Acoustical phenomena associated with curved surfaces can introduce entertaining auditory characteristics in a space, for example the presence of an echo (distinct and late repetition of a sound) or the so-called whispering galleries (multiple reflections travelling distances along a curved surface). An early example can be found in ‘Phonurgia Nova’ (Kircher, 1966), a curved geometry is described that causes a sound amplification and increased speech intelligibility between two points, in an unexpected way.

With the introduction of wave theory of optics (Huygens, 1690), the acoustic behaviour can be modelled following principles of optical geometrics, in which rays are used to demonstrate wave propagation; that is, sound is treated similar to light by which the exit angle of a ray reflecting from a surface equals its complementary entrance angle with respect to the normal of the surface. Different concentration patterns result as the geometry changes from a circle to an ellipse. In spaces with a circular ground plane (with a centre based sound source), sound rays meet the wall at same time, are reflected, and a sound wave will converge simultaneously upon the original source position. Sound waves that form a successive wavefront through secondary sound reflections will result in sound concentration at a particular point (Cremer and Mueller, 1982). Furthermore, rays in an ellipsoid will concentrate in two opposite focal points.

In complex designs with a spherical morphology, sound concentration caused by curved surfaces can cause uneven sound distribution in the audience area, and lead to negative effects such as low speech intelligibility, specifically as reflection

characteristics are exacerbated by the use of hard materials. Surfaces curved in two directions such as spheres or ellipsoids would usually result in strong sound focusing which negatively affect the acoustic experience. This poses an evident problem in spaces that require good listening conditions, as is the case in temporal art (Cremer and Mueller, 1982; Vercammen, 2012). We understood this as a challenge to revise directly complex curved geometries through iterative revision and innovative use of parametric and analytical design methodologies, undertaking a research that demonstrates that acoustic performances in ellipsoidal spheres can be acceptable if the geometry is integrated with acoustic simulation.

4. Sonic Domes: Case Study

The problem of acoustic behaviour of complex curved surfaces in an architecture based on complex intersecting ellipsoid spheres is revised in the proposal for a cultural centre in Nagano prefecture, Japan (Figure 1), designed to withstand the seismic and environmental effects of the region, lateral force waves of earthquake scenarios and vertical stress by extreme exposure to temporary snow loads (3.3m equal 1t/m^2). This context deviates from classical temporal arts spaces through a multifunctional design brief, whereby acoustic behaviour is an integral but nonexclusive parameter. 'Sonic Domes' is modelled as a series of intersecting spheres, to answer requirements of structure and performance, in contrast to single ellipsoidal sphere sections that commonly define stage and auditorium spaces in temporal arts.

Structurally, the design proposes a dome as an ideal formation for earthquake secure buildings. This responds to structural requirements of extreme stresses as caused by temporary imposition of loads, based on a circular geometry with a centre of gravity oriented in the lower section. Spatially, the interlocked ellipsoidal spheroids allow a dynamic flow of varying spatial volumes that can be adapted to temporary programmatic requirements, with fluent transitions between internal intersections and adjacency of zones. The processes of developing the project between the different team members proceeded as iterative design and analysis through different

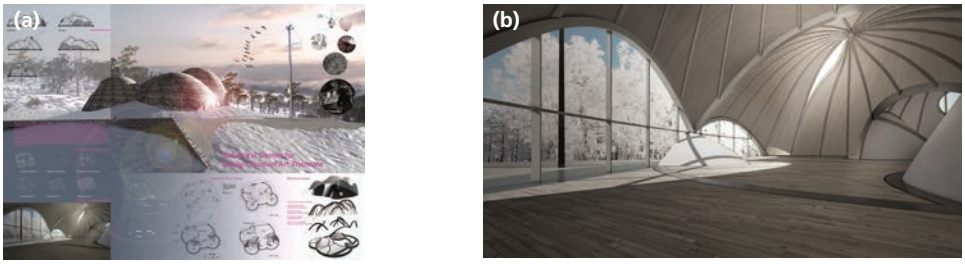

Figure 1. Sonic Domes, competition panel (a) and Interior Perspective (b).

steps at which end data were exchanged; from (1) construction of intersecting spheres in 3D modelling software (McNeel Rhino); to (2) an initial acoustic analysis to identify position of sound source in major volumes (ODEON); back to (3) parameterization of structural system to deflect geometry (McNeel Plugin Grasshopper); to (4) finite element analysis of structure (Strand7); and (5) evaluating final acoustic simulation (ODEON). In this 'reverse engineered' process, the acoustic forecast becomes the descriptor for formal, perceptual and structural solution.

5. Loop 1: 3D Modelling and Initial Analysis of Curved Surface Geometry

'Sonic Domes' is constructed as ellipsoidal spheres in 3D modelling software, whereby spheres with varying dimensions (resulting in major and minor volumes) are inscribed as intersecting rings of steel in base plan, with a calculated potential to absorb lateral seismic forces. The primary supporting steel columns arise as three-dimensional cross bracing from the base intersections, and define embedded triangulated spatial cores. A secondary structural system of plywood timber beams complements beams and articulates each sphere, and its intersection on the base plane, and three-dimensionally along the curvature of the spheres. A tessellated system of planar elements (timber shingles) forms the exterior skin, following the surface curvature (Figure 2, a). In the main volumes, the ideal geometry of intersecting ellipsoidal spheres is manipulated along the centre section line, so that the resulting geometry opens at the upper part to let natural light in (Figure 2, b).

The spheres follow the logic of force-response of ideal catenaries structures (b = h+a, ie 1/2b>a for optimum). The performance of curvature was initially assessed by the architect through a number of criteria; the overall intersection of spheres; the distribution of seams and openings; the homogeneity within radii; the Gaussian Bell Curve distribution; and default points within the surface curvature

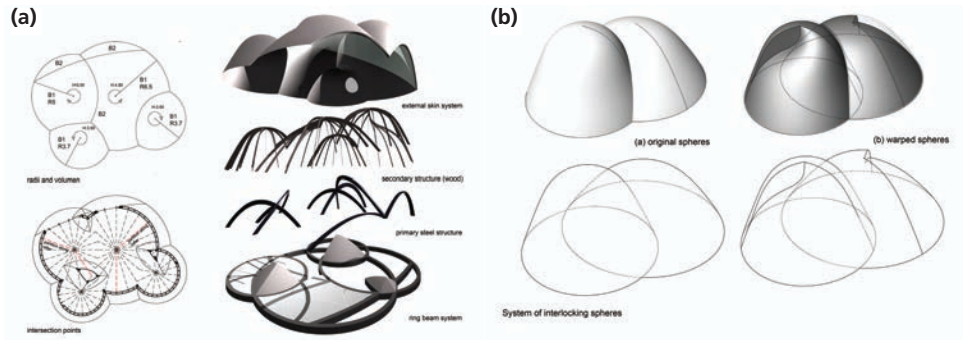

Figure 2. 3D model with base plate, spheres and structural beams (a), system of interlocking spheres and manipulation of curved geometry (b).

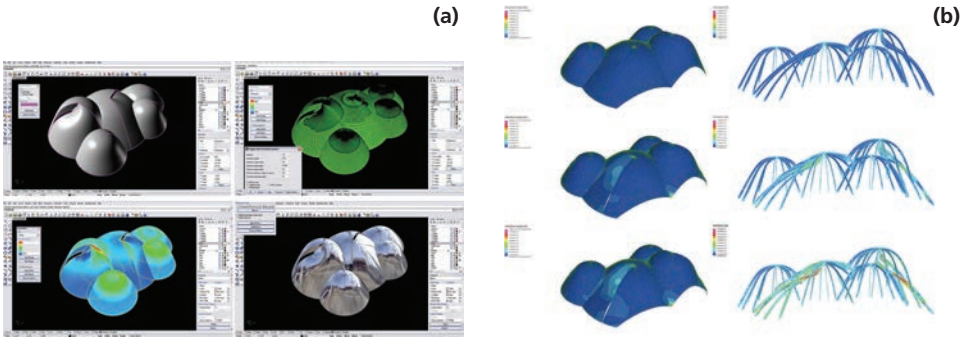

Figure 3. (a) Surface Behaviour (Rhino), and (b) FEM analysis for shell and beams (Strand7).

under high light reflection; and possible solutions for planar tesselation (Figure 3, a). The resulting data were exchanged with a structural engineer. A Finite Element analysis in Strand7 compared stress behaviour in the spheres modelled as rigid shell structure, and as beam system (Figure 3, b). A beam system would be more readily constructed, expected to be more cost effective and would incorporate steel and timber framing elements for reduced mass and improved ductility and performance in an earthquake event in comparison to a concrete shell structure. The result identifies that while an efficient structural performance can be achieved in both cases, the beam system requires also the insertion of a rigid frame for the openings in order to address critical moments in the sphere.

With the structural requirements solved, the programmatic brief included a requirement of unamplified vocal performances, with even distribution of sound levels across the entire audience area. Providing a similar experience to all audience members with high speech intelligibility at all locations within the audience area was an important acoustic parameter in the design process. Given that the problem of sound concentration in curved surfaces was well known, the design had to be tested for its acoustic performance. The next step was an initial analysis, whereby the original 3D data (Rhino) were exported as 3dsfiles (3DStudioMax) to acoustic modelling software (ODEON), where they were parameterized and sufficiently segmented to allow a close acoustic analysis. In a spherical geometry, rays are concentrated in a focus point, with a uniform distribution, where propagation distances of sound paths are described as equal depend on the particular point the performer takes. We tested two source positions in a deflected geometry (spherical deflected dome with opening), in order to understand how sound rays reflected when positioned in the major volumes, and to test the resulting speech intelligibility (Figure 4).

While the expectation was that the sound would concentrate negatively through reflections and sound concentration, the acoustic simulation showed the intersected domes not only proved an ideal formation in structural analysis, but

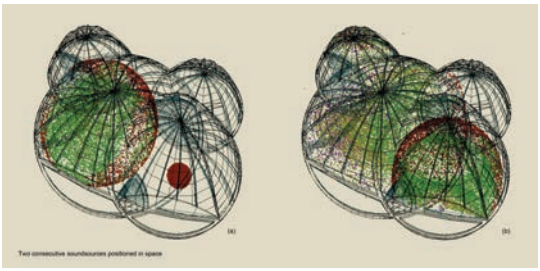

Figure 4. Initial acoustic analysis, two source positions.

also their acoustic behaviour was acceptable – taking into account that the original geometry of the sphere was deflected, and the sources were ideally positioned.

6. Loop 2: Final Specification of Curved Surface Geometry through Acoustic Behaviour

In order to test the outcome of different architectural configurations, several parameter changes of the original sphere geometry were scripted as height and diameter variations, and as shift of central sphere point in the original ideal sphere shapes: several more variations were developed in a scripting environment (McNeel Plugin Grasshopper), to identify changes in acoustic behaviour as response to variations of the system geometry (Figure 5, a and b).

These generative form variations went through a subsequent acoustic simulation (ODEON), taking into account a deflected shape of spheres in which the centre point of the dome is shifted. This was done in order to establish visual references for the relationship between manipulations of geometry, and the resulting acoustic behaviour. This second acoustic simulation was run using the optimised stage position originated from the results of the first analysis (with sound centre based in

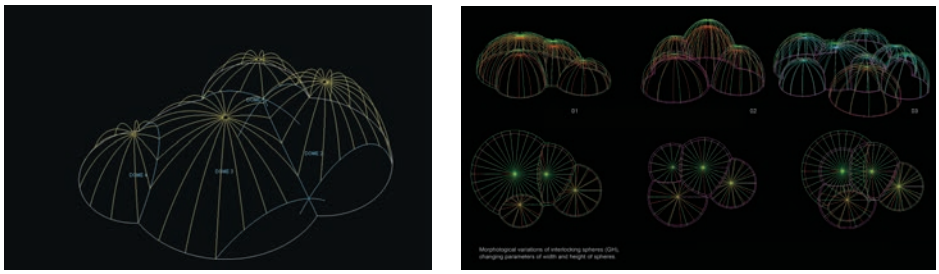

Figure 5. (a) system parameterization (height, diameter variations in Grasshopper), and (b) Morphological variations of interlocking spheres.

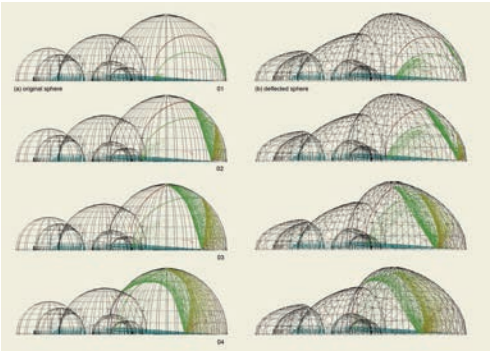

Figure 6. Second acoustic analysis verifying acoustic behaviour by comparing original and warped geometry (shifted centre point).

largest dome, configuration as spherical shape, centre equidistant to circumference). The results show the ideal dome with a steady state high sound concentration in a small area and uneven sound distribution across the entire audience area, and a deflected dome (Figure 6) with a centre of sphere to an elliptical shape, which shows level variations across the audience area as smaller, thus providing a better coverage of the entire audience area – a better acoustic performance.

To quantify the acoustic variations, sound pressure level (SPL_A) is used as a descriptor of level across the audience area and Speech Transmission Index (STI) (Steeneken and Houtgast, 1980) is used to quantify speech intelligibility across the audience area for both configurations (Figure 7). In the original domes, speech intelligibility is high in the areas where the sound concentration happens, and diminishes closer to the enclosing walls, resulting in unacceptable speech intelligibility at several locations. In the deflected dome, an overall increase in speech intelligibility as well as an even distribution of sound level across the audience area can be seen.

Furthermore, this shape supports even distribution of reflections across the audience area. By bringing the back wall closer to the performer, useful reflections arriving at an early stage aid in raising the speech intelligibility across the audience area. A summary of the results for the original and warped dome configurations (Figure 8) is presented as numerical data, which shows the overall tendency of the results, as well as the distribution across the area. In the STI results, the warped dome configuration shows clearly that STI values are higher overall, and that the distribution is centred around a higher mean. The SPL results show that the occurrences in a certain histogram bin have a higher count, representing the even response in level across the audience area.

The extended acoustic analysis thus confirmed that specific characteristic of deflected curvatures in the intersecting spheres of the competition design resulted in good acoustic conditions, as opposed to a more classical approach of standard

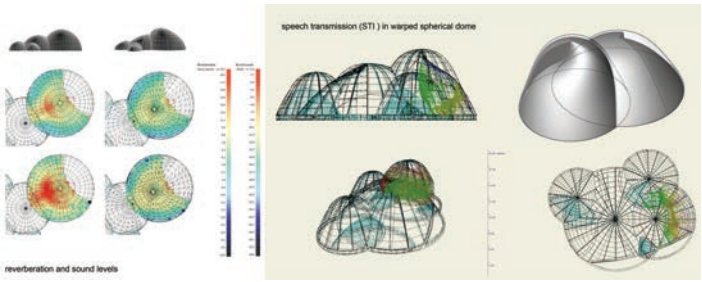

Figure 7. (left, up) SPL A-weighted at audience area and (left, down) STI at audience area; each showing original spherical configuration and deflected dome; (right) section through deflected sphere.

ellipsoid spheres. Sound concentration in curved surface geometries can be further be managed in a micro topography (adapting direction, scale and smoothness of reflective segments), but in this case, the iterative interdisciplinary exchange confirmed that performance was significantly informed by the macro topography of overall surface geometry (adapting heights, position of centre points, dimension and curvature).

7. Conclusion

The paper has discussed a design solution to the problem of sound concentration in complex curved surfaces; by improving the acoustic behaviour through redirection of reflected sound. Through implementation of an interdisciplinary and iterative exchange between areas commonly separated through steps in the design process, better speech intelligibility and enhanced acoustic performance could not only be taken into account at an early stage, but moreover the intersection between computational design, structural analysis and acoustic simulation solved the problem sound concentration in complex curved geometry to such an extend as to support the preferred design decisions.

The paper introduced an iterative design, analysis and optimization processes, in which a number of generative form variations were developed in computational 3d modelling software (McNeel Rhino), variations developed as rule-based (Grasshopper), tested in engineering software (Strand7), and evaluated in acoustic simulation (ODEON). The investigation revealed that the structural deflection of original spherical geometry, and resulting sound reflection in relation to curvature of the space enhances the acoustic performance of the space. The design communication between disciplines enabled us thus to identify both the acoustically best positions for sound production (stage area) and acoustic experience (audience area), and it validated a geometry without relying on secondary absorption or

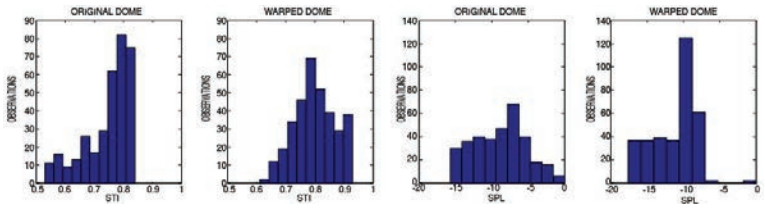

Figure 8. Histograms of STI and SPL across the audience area for the original and warped dome configurations.

amplification measures. While curved surfaces are not usually recommended for performance spaces, the integration of generative design, structural and acoustic analysis provided good acoustic results by a deeper understanding of relationships between structure, space and sound.

In that manner, the final design solution carefully balances a diversity of requirements, from external force impacts, to interior sound fields. By interlinking knowledge, methodologies, expertise and software of different design realms, an open system is generated in which communications and transfers between team design and collaborative approaches are combined and inform each other.

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References

Cremer, L. and Mueller, L.: 1982, *Principles and Applications of Room Acoustics*, Applied Science, New York.

Huygens, C.: 1690, *Traité de la lumiere*, Pieter van der Aa, Leiden, Netherlands.

ISO: 2009, Acoustics – Measurement of room acoustic parameters, ISO 3382-1:2009.

Kircher, A.: 1966, *Phonurgia Nova*, Broude, New York.

Langhans, C. F.: 1810, *Ueber Theater*, Julius Eduard Hitzig, Berlin.

Reinhardt, D., Martens, W. and Miranda, L.: 2012, Acoustic Consequences of Performative Structures- Modelling Dependencies between Spatial Formation and Acoustic Behaviour, *Digital Physicality*, Faculty of Architecture, Czech Technical University, Prague, 577–586.

Steeneken, H. J. M. and Houtgast, T.: 1980, Physical method for measuring speech transmission quality, *Journal of the Acoustical Society of America*, **67**(1), 318–326.

Vercammen, M.: 2012, Sound Concentration caused by Curved Surfaces, PhD Dissertation, Eindhoven University of Technology, Eindhoven, Netherlands.

CITY MODELLING

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OPEN TO RIDICULE

Deploying plaything technology for 3D modelling of urban informal settlements in Asia

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Abstract. As technology affine urban landscape researchers, working in Asian mega cities, we roam through crowded and narrow, widely informal city layouts, where we apply digital fieldwork equipment and conduct design work. We use low cost cameras and camera drones, tools that had been developed as gadgets for outdoor freaks or plaything for nerds. In this paper, we describe recent advances in the development of a method of on-site data and image gathering, which allows the processing of concrete 3D models of informal city spaces. The visual quality of these models is still moderate, but the resulting three-dimensional spatial puzzle makes a widely inaccessible and undocumented piece of city terrain visible, understandable and designable. The software used is free.

Keywords. Fieldwork tools; mapping; 3D modelling.

1. Investigation Area

Kampung Melayu-Bukit Duri is an urban village in East Jakarta, situated at both sides of the Ciliwung River. The river is prone to floods of cataclysmic proportions, and is heavily polluted (Figure 1). We are investigating this area in the

Figure 1. In the foreground the specific riverbed profile consisting of a metre-thick mix of waste and sediment can be seen (Photo: Rekittke, 2011).

course of the research module Landscape Ecology in the 'Future Cities Laboratory' (Rekittke and Girot, 2012), hosted and managed by the Singapore ETH Centre for Global Environmental Sustainability (Cairns et al., 2012).

2. White Spots on the Digital World Map

In order to build complete and detailed models of complex terrain and urban territory, the direct contact to ground and detail remains indispensable – for all the available remote sensing technology. Those who depend on the direct and real-time contact to site and substantiality, we refer to as 'foot soldiers'. Those who work from the distance, we refer to as 'aviators' (Rekittke et al., 2012).

> Being a foot soldier [...] does not mean that the chosen equipment is not related to the mother technology of the aviators – satellites, radio, and data networks – rather, it has to be light, portable and inconspicuous. [...] Their mission is to provide for terrain data and details that cannot be gathered by the aviators [...]. (Rekittke et al., 2012, p. 199)

Foot soldier craft is appropriate to sort out remaining white spots on the digital world map, situated under vegetation and urban canopy like roofs, architectural overhangs, superstructures and in urban canyons, where remote sensing technology proves to be blind (Figure 2). Where we work, no one hands out any expedient data to us, suitable for copy and paste transfer to our computers. Furthermore, the speed of change within the context of megacities accelerates the expiry date of the little available material. Design research needs up to date data for spatial analysis and academic design studios often operate on a low-cost and low-key level. We subsume such approach under the term of 'Grassroots GIS' (Rekittke and Paar, 2010).

Figure 2. Under the bridge (bottom of image) 200 people are living; the Ciliwung River edges are submerged, canopy camouflages the terrain (Image: Google Earth, 2012).

3. Direct Landscape Exploration with Unorthodox Equipment

The fieldwork at hand took six days, focussing the river and its edges. Initially we walked along the banks, but our feet sank too deep into the sludge and the banks became too steep for walking. In order to model 2.86 km of the river stretch, we had to get onto the river. A *Challenger Inflatable*, the mother of all rubber boats was purchased (Figure 3), ideal for rafting between the floating toilets and trash of the Ciliwung River. It carries four people and a load of 400 kg. We carried a *Garmin* GPS tracking device, for digital video taking we used three combined sets of the *GoPro HD Hero2 Outdoor Edition* – off the shelf action video cameras fitted in waterproof housings and attached to 3-way pivots on a telescopic mast (Figure 4).

Figure 3. Garmin GPS track loaded and visualised in Google Earth with accompanying elevation data expressed as the graph. Measurements displayed – the Garmin is imprecise – include relative height, speed and duration of the boat trips (Images: Ninsalam/Paar, 2012).

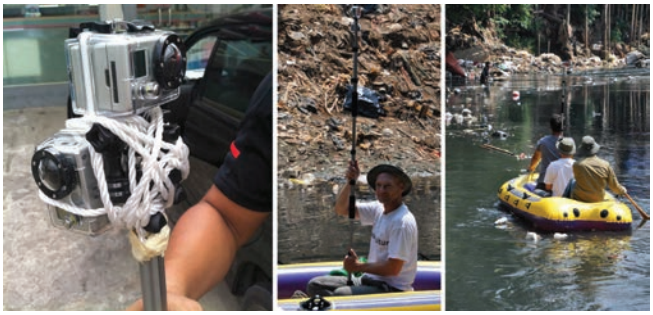

Figure 4. Requisite handicraft work: three GoPro HD Hero2 cameras, mounted on a telescopic mast, balanced in the middle of the flabby boat (Photos: Rekittke/Heng, 2012).

Figure 5. Drone takeoff from the boat. The video quality of the inbuilt camera is moderate (Photos: Paar, 2012).

The GoPro camera captures high-resolution videos and photos with a 2.8 mm fix objective. For the recording of the river trips we chose the 127° medium field of view (FOV) setting with a resolution of 1920 x 1080 pixels, and a rate of 30 frames per second. A tropics-specific problem had been the occasional overheating of the cameras, caused by prolonged usage in the waterproof housing. This contributed to a partial loss of initial recordings before the detection of the issue.

In order to *visually illuminate* completely inaccessible or hidden areas of the site, we carried an iPad-app-controlled *Parrot AR.Drone 2.0* (Figure 5), being about an inexpensive plaything quadrocopter with an effective range of about 50 meters, equipped with an in-built video camera, allowing wireless video recording and transmission via a picture resolution of 1280 x 720 dpi, a 92° diagonal wide angle lens and a recording rate of 30 frames per second.

The drone is remote controlled by the gratis *AR.Free Flight* app, which records and transmits data to control three sensory functions of the aircraft: 1) yaw, pitch and roll movement; 2) ground altitude; 3) x/y axis ground movement. When taking

off from a steep and uneven riverbank, the drone initially worked well and delivered precious video material but later displayed an *Ultrasound Emergency*, presumably due to the dusty uneven terrain, and finally crashed. When launched from the boat, things went unexpectedly well. The drone flew smoothly and captured acceptable video recordings – *quod erat demonstrandum*. During the final attempt the drone shaved some bamboo leaves, struck an open toilet pipe of a slum shack and miserably crashed into a feculent garbage heap.

4. Post-processing with Free Software Components

The hardware we use for post-processing represents common standards in computer gamer circles – *Grassroots GIS* asks for affordable off-the-shelf articles. All software applied for the described work is free or open source. For the post-processing of former fieldwork material we used the web-based software *Autodesk 123D Catch* that allows for an upload of less than one hundred photos. This time, we experimented with uploads of up to three thousand photos simultaneously, via the programmes *VisualSfM version 0.5.20* and *CMPMVS version 4.0*. VisualSfM is a graphics user interface (GUI) application of Structure from Motion (SfM) (Wu, 2011). The system is based upon the measured correspondence of image features, such as points, edges and lines – inferring camera poses from a selection of photos (Wang, 2011). Subsequently, the measured camera poses are processed by CMPMVS, multi-view reconstruction software, which generates a textured mesh and reconstructs the surface of the final 3D model (Havlena et al., 2010). The resulting product of VisualSfM – a point cloud – then can be processed with the help of CMPMVS. The standard workflow (Figure 6) for VisualSfM and CMPMVS can be abstracted as follows:

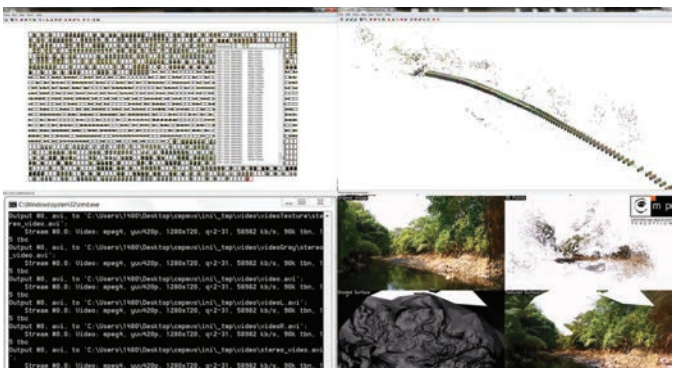

Figure 6. VisualSfM workflow: Feature Detection and Bundle Adjustment (top left and right); Dense and Surface Reconstruction in CMPMVS and video output (bottom left and right).

- Upload of the images into the SfM workspace as an image file in jpg-format.
- Feature detection and full pairwise image matching, this generates a set of measured image features and correspondence (Wu, 2007).
- Incremental reconstruction, this will start the multicore bundle adjustment, which calculates the 3D point positions and camera parameters from the set of measured image features and correspondence (Wu et al., 2011)
- Dense reconstruction by using a multi-view stereo (MVS) application – CMPMVS – this performs the textured surface reconstruction from the point clouds (Havlena et al., 2010).

5. Choice of Optimal Software

The Autodesk software *123D Catch* offers limited functionality concerning a detailed determination of the resulting model, but it is the best choice for basic users. Features that hitherto outplay *VisualSfM* include the implementation of a reference scale allowing scaling of the entire 3D model, taking of reference measurements, animation of the 3D model in the software directly, and a complete, cloud-based 3D surface reconstruction pipeline. VisualSfM stores and processes the selected image material on a local folder. This bypasses any time consuming and often impractical web-based upload and enables the user to check feature matching and sparse reconstruction processing in the field. The main goal of our research is to achieve the best model quality possible. VisualSfM therefore currently turns out to be the optimal option (Figure 7).

The pipeline allows for a flexible addition of selected photos to integrate and improve existing models. It also allows manually performed initialization of the automatic feature detection process by the determination of a proper pair of photographs. A ‘Pause’ and ‘Run’ button facilitates the integration of more photos during the feature-matching phase.

Figure 7. Screenshot of a model generated from Autodesk 123D Catch (left); screenshot of the same model generated from VisualSfM (right).

6. Choice of Optimal Picture Capturing Method

The quality of the used image material is closely related to the choice of equipment and capturing methods. In combination this defines the quality of the final model. We experimented with both photo taking and video filming.

In order to produce still photos from the site we use common standard DSLR cameras, which deliver imagery of very high resolution. Our video material was generated by *GoPro HD Hero2* action cameras and *Parrot AR.Drones 2.0*. The action cameras were initially made for sports freaks like free fallers, bungee jumpers and other contemporaries tired of life and keen to document their adrenalin-warped faces or bird's eye view environments during flight. The inexpensive drones are considered to be gadgets. The technology of these devices is developing fast and will achieve impressive functionality and quality soon. The use of the chosen tools is practical in harsh environments and small budget contexts. When using site photos, all available images are fed into the respective *black box* – 123D Catch or VisualSfM. Video format recordings cannot be fed into the system in an unprocessed form, a certain number of frames have to be extracted. In order to find out the adequate number of extracted frames, we had to carry out tests. For this purpose we defined a one hundred seconds sequence of the river, approximately covering a leg of eighty meters. Our initial hypothesis reads that the bigger the number of extracted frames, the better the models would be. This assumption turned out to be unfounded. The most successful model quality results from a feed-in range between one to five frames per second (Figure 8). The camera

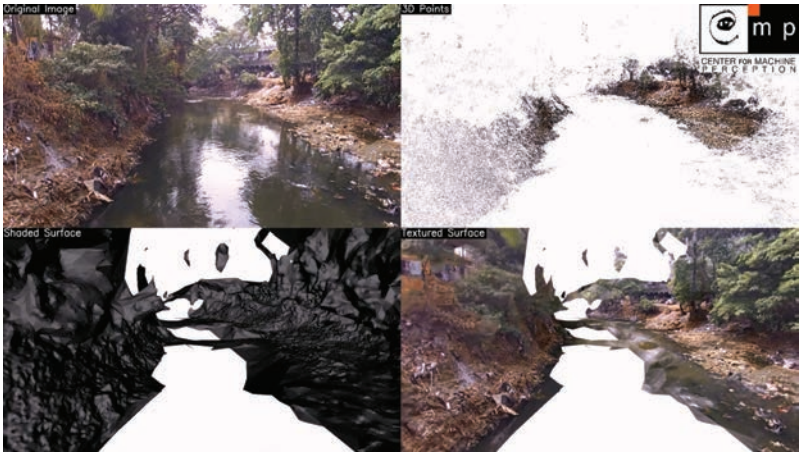

Figure 8. Less is more: CMPMVS screenshot of a landscape model at one frame per second feed-in rate, representing the actual quality we are able to generate with our low-cost tools.

records thirty frames per second, accordingly, a five frames per second selection implies the use of every sixth frame.

7. State of the Art

While we worked on the post-processing methods in our project, the *Street View* producer Google announced a field campaign which definitely marks the current high-end reference and benchmark related to our moderate foot soldier approach. The company mounted its expensive camera technology on a backpack – showcasing the Grand Canyon's most popular hiking trails.

> The so-called trekker captures images every 2.5 seconds with 15 cameras that are 5 megapixels each [...]. The GPS data is limited, so Google must compensate with sensors that record temperature, vibrations and the orientation of the device [...], before it stiches the images together and makes them available to users [...]. (Fonseca, 2012)

The used rosette of cameras (Figure 9) is the latest evolution in mapping technology made by the Mountain View Company, California.

Figure 9. The 'trekker' during a demonstration at Grand Canyon National Park. The device weighs about 18 kilograms, it is about 1.2 metres in height (Photos: AP/Rick Bowmer).

8. Benefits and Limits of Plaything Technology

The rubber boat represents an openness to ridicule, as does the plaything drone that we had aboard. One of our main benefits of these playthings unquestionably is the fact that we never would have dared to apply the described technology and methods in the given environment, if they would have been subject to high expenditure and material value. The price we pay for the low-cost solution is the limited model quality we can currently achieve. The front camera objective features such

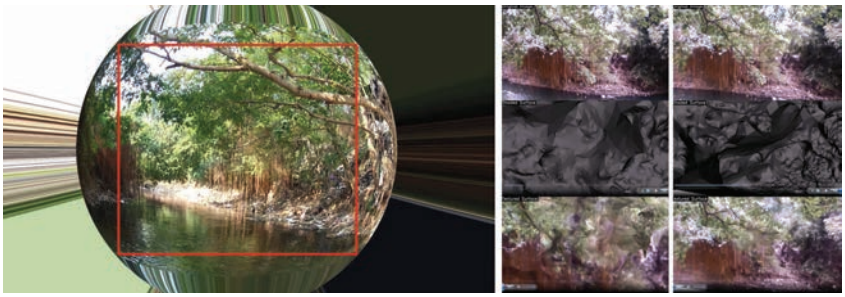

Figure 10. Results from an AR. Drone 2.0 flight: (left) faulty model after auto-rectification of barrel distortion in VisualSfM; (right) original image–shaded surface–textured surface series without radial distortion (l.) and with distortion option turned on (r.).

a large distortion error value that it has to be auto-rectified by the software VisualSfM. The drone camera is too low-grade to be calibrated for radial distortion with the help of existent software. There are sundry software-based possibilities to bypass such demerits, but in our work we deliberately do not aim for perfection. In the context of our academic design research studio work with students, even a deficient model makes sense and is better than nothing (Figure 10). However, the better the available and chosen camera technology will become, the better the quality of the producible models will be.

9. Foot Soldier Future

The craft of the fieldwork conducting foot soldier will remain shirtsleeve, what will rapidly change are precision, accuracy and dependability of the available equipment. The complexity of operations will have to be increased, from the current image-based modelling approach towards a conflation of GIS data sets and their corresponding image-based geometries. Conflation – in GIS – is defined as the process of combining geographic information from overlapping sources in order to retain accurate data, minimize redundancy, and reconcile data conflicts (Longley et al., 2001). We already ordered the next generation of outdoor action cameras – insignificantly more expensive but considerably more powerful. Also, an improved aircraft will be in our baggage. One day, when the price drops, a portable 3D scanner system with real-time 3D reconstruction capability might be part of our equipment. These scanners come with software development kits, which enable developers to create various new applications (Andersen et al., 2012). And certainly one must experiment with Light Detection And Ranging (LIDAR) technology, which is being integrated into standard GIS software

(Jordan, 2012). With the help of these advanced tools, many of the remaining white spots on the digital world map will be successfully filled with three-dimensional information.

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References

Andersen, M.R., Jensen, T., Lisouski, P., Mortensen, A.K., Hansen, M.K., Gregersen, T., and Ahrendt, P.: 2012, *Kinect Depth Sensor Evaluation for Computer Vision Applications* (Technical Report ECE-TR-6), Department of Engineering, Aarhus University, 1–39.

Cairns, S., Gurusamy, S., Prescott, M., and Theodoratos, N. (eds.): 2012, Rivers in Future Cities: The Case of Ciliwung, Jakarta, Indonesia. Module VII: Landscape Ecology, *FCL – Future Cities Laboratory Gazette*, **12**, Singapore ETH Centre for Global Environmental Sustainability.

Fonseca, F.: 2012, Google cameras map popular Grand Canyon trails. Associated Press, Oct 24, 2012. Available from: <http://bigstory.ap.org/article/google-cameras-map-popular-grand-canyon-trails-2> (accessed 23 November 2012).

Havlena, M., Torii, A., and Pajdla, T.: 2010, Efficient Structure from Motion by Graph Optimization, *in* Daniilidis, K., Maragos, P. and Paragios, N. (eds.), *ECCV 2010, Part II, Lecture Notes in Computer Science (LNCS) Volume 6312, 2010,* Springer-Verlag, Berlin, Heidelberg, 100-113.

Jordan, L.: 2012, "Integrating LiDAR and 3D into GIS". Available from: <http://www.youtube.com/watch?v=0USiCcsiFqE> (accessed 25 November 2012).

Longley, P.A., Goodchild, M.F., Maguire, D.J., and Rhind, D.W.: 2001, *Geographic Information Systems and Science*, John Wiley & Sons, New York.

Rekittke, J. and Girot, C.: 2012, Cali Ciliwung Experiment, *S.L.U.M. Lab*. Sustainable Living Urban Model, Edition **7**, 68–69.

Rekittke, J., Paar, P., and Ninsalam, Y.: 2012. Foot Soldiers of GeoDesign, *in* Buhmann/Ervin/Pietsch (eds.), *Proceedings of Digital Landscape Architecture 2012*, Anhalt University of Applied Sciences, Wichmann, Heidelberg, 199–210.

Rekittke, J. and Paar, P., 2010. Grassroots GIS – Digital Outdoor Designing Where the Streets Have No Name, *in* Buhmann, E., Pietsch, M., and Kretzler, E. (eds.), *Proceedings of Digital Landscape Architecture 2010*, Anhalt University of Applied Sciences, Wichmann, Heidelberg, 69–78.

Wang, Y.-F.: 2011, *A Comparison Study of Five 3D Modeling Systems Based on the SfMPrinciples* (Technical Report No. Visualsize Inc. TR 2011-01), Goleta, USA, 1–30.

Wu, C.: 2011, "VisualSFM: A Visual Structure from Motion System". Available from: < http://homes.cs.washington.edu/~ccwu/vsfm/> (accessed 3 November 2012).

Wu, C.: 2007, "SiftGPU: A GPU implementation of Scale Invariant Feature Transform (SIFT)". Available from: < http://cs.unc.edu/~ccwu/siftgpu> (accessed 1 November 2012).

Wu, C., Agarwal, S., Curless, B., and Seitz, S.M.: 2011, Multicore Bundle Adjustment, *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition 2011* (CVPR), 3057–3064.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 551–560. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

CAPTURING URBAN INTENSITY

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Abstract. While the methods for capturing the negative effects of density (e.g. congestion, friction) are widely understood and operationalized, capturing the positive effects of density (e.g. vibrancy, walkability) remain poorly explored. This research focuses on the latter, proposing a novel spatial analysis and mapping approach that can be used to capture the intensity of urban environments. We distinguish between urban density and intensity. Whereas density refers to the amount of people or elements of urban form (e.g. dwelling units, floor area) per unit area of land, intensity refers to the concentration of commercial and service activities on the ground floors along city streets. Bridging morphological mapping techniques with recent network analysis in GIS, ten metrics that capture specific attributes of the built environment influential to intensity are introduced and implemented using data collected from detailed field surveys within two comparative districts in the Bugis area of Singapore. A discussion of the efficacy of these metrics for urban design concludes the paper.

Keywords. Urban intensity; density; built environment modelling; urban design; surveying.

1. Introduction

"The charged void" describes "architecture's capacity to charge the space around it with energy, which can join up with other energies, define the nature of things that might come, anticipate happenings… a capacity we can feel and act on, but cannot necessarily describe or record" (Smithson and Smithson, 2005).

What Allison and Peter Smithson called the "charge" of urban spaces summarizes a set of place qualities that shape the activities and happenings that occur, or have a potential to occur, between a city's buildings. The Smithson's "charged void" refers to complex relationships that link the physical configuration of urban space to both the activity patterns and opinions of its users – qualities that are of great importance to any city.

The authors go on to argue, however, that these relationships can be felt and acted on by experienced practitioners, but not captured analytically. Any particular interaction between form and use in a place is likely to be neither unique nor deterministic. Instead, the relationship can take many forms and depend on a range of additional factors that affect people's use of space beyond spatial form.

While it is now generally accepted that spatial configuration is not the dominant – nor by any means the only – force affecting the life between buildings, its effect on the quality of a place cannot be ignored. Spatial analysis techniques have come a long way and offer a unique opportunity to revisit the challenges of describing and analysing the "charged void" empirically. The need for an empirical understanding of the environmental factors that affect, and desirably benefit, the nature and distribution of human activities on streets is further compelled by the rapid construction and redevelopment of cities, whose significant physical transformations could result in as significant social transformations.

The Bugis district in Singapore, which currently undergoes another redevelopment cycle, offers an exemplary case for such empirical study. Two typological samples of urban fabric chosen in the Bugis area, both considered to be intense urban places in Singapore, embody contrasting traces of built form and densification strategies from different eras of the city's urban development. While one reflects the urban patterns of pre-1960s with its predominantly old, low-rise shop house typology, the other contains densely spaced larger commercial buildings, with several floors of complex indoor shopping networks. The latter is indicative of the direction in which contemporary practice of urban design and planning is moving in the Bugis area. Thus, the main reason to compare these two samples of urban tissue is to show not only how each of them generate different levels of intensity, but also to anticipate the spatial qualities that present and future urban development is likely to bring to this area.

It is well known that denser city environments tend to generate higher levels of interaction between people, establishments, and institutions than sparser city environments (Avent, 2011; Salmon, 2012). But density alone is insufficient to warrant desirable interactions for living, working and recreation. It is often the subtle differences in the quality, not quantity, of interactions, which make one city or neighborhood more attractive than another (Larice, 2006). The quality of streets depends as much on the gross quantities of people, jobs and business establishments around them as it does on the planimetric arrangement of built form that mitigates

access between these actors. The configuration of paths between buildings determines the conditions of adjacency and proximity between the tenants of an area and its public spaces, setting them up to be encountered by many or to be hidden from movement and view (Hillier and Hanson, 1984; Porta et al., 2009; Sevtsuk, 2010). The capacity of ground floors – the immediate interface between outdoor public space and indoor space that Anderson (1978) has called "occupiable" – to accommodate a wide range of activities and to generate inviting entrances towards passers-by directly influences the character of a street (Jacobs, 1993; Gehl, 2010). The ground floors and their perimeters not only affect the operations of activities that they currently accommodate, but also set the approximate limits to what activities could come to occupy them in the future (Aylward, 1969; Habraken, 1999). A number of scholars have searched strenuously for measurable propositions that link spatial form with the qualities of urban environments, prior to our research (Southworth 2003; Clemente et al., 2005; Ewing et al., 2006; Talen and Duany, 2006a, 2006b; Forsyth et al., 2010).

This paper investigates how both the configuration of urban form and street edges affect the vibrancy of two comparative areas around Bugis (Figure 1). We first explore how to measure the vibrancy of both sites – the "charge" they contain – using a network-based accessibility metric that estimates walking to surrounding commercial destinations in a given access radius. We subsequently discuss how the configuration of urban form affects the availability of destinations and the quality of walking routes that lead to them.

2. Capturing Intensity

We distinguish between urban density and intensity. Whereas density refers to the amount of people or elements of urban form (e.g. dwelling units, floor area) per unit area of land, intensity refers to the concentration of commercial and service activities on the ground floors along city streets. We call this ground floor quality intensity, since it describes the interface of the urban environment that people sense most directly and encounter on a daily basis. Our definition of urban intensity refers to the volume of spatial interactions that the ground floor of a district has to offer – street networks that accommodate higher concentrations and more diverse activities are considered more intense.

By activities along streets we refer to both economic establishments and individual actors that conduct business on the area's streets. Economic establishments contain retailers, service establishments, restaurants and drinking places, which offer their goods and services on a regular basis. Individual agents, on the other hand, denote vendors, street performers, and service providers (e.g. food kiosks) that do not have a permanent shelter for their activity and typically operate from mobile counters.

We capture the concentration of activities around a particular location using an accessibility metric. There are a number of accessibility metrics that could be employed for this purpose (Bhat et al., 2000; Sevtsuk and Mekonnen, 2012). The Urban Network Analysis toolbox, operating in the ArcGIS environment, allows one to quantify how many and what types of amenities are reachable on foot from a particular location on the network, as well as to capture the spatial qualities of the routes that lead to these amenities.

The *Reach* accessibility of a location describes the number of specified destinations that can be accessed from a particular location within a given access range. The reach centrality $Reach^r[i]$ of a location i in a network G at a search radius r, describes the number of destinations in G that are reachable from i on a shortest path distance of at most r. It is defined as follows:

$$Reach^r[i] = \sum_{j \in G - \{i\}; d[i,j] \leq r} W[j] \quad (1)$$

where is the shortest path distance between location i and destination j in network G, and $W[j]$ is the weight of a destination j (Sevtsuk and Mekonnen, 2010). The weights can represent any numeric attribute of the destinations – their size, the number of employees they contain, their attraction level etc.

When estimating accessibility to economic establishments and mobile vendors around a location, the set of destinations j in the *Reach* index can be specified to capture only these types of establishments, ignoring other uses like offices. The network radius r can be set to a distance that captures the accessibility to destinations within a desired intensity measurement range. We are interested in capturing accessibility in an immediate 3-minute walking range around both study locations, and therefore use a radius of 200 meters in our estimates that follow.

The *Reach* accessibility to commercial establishments can be affected by three distinct qualities of urban form. First, the measure can increase if the destination buildings that the index is computed to are larger in volume and accommodate more establishments. Second, if the number of neighbouring buildings rises, that is, if we observe a denser spacing between buildings per linear length of street segments, keeping building sizes and the geometry of the street network constant, then *Reach* to destinations can also rise. And third, if we keep the spacing of buildings and the sizes of destinations constant, then the *Reach* measure can also increase if the origin is located at a more connected juncture of a street network, where more streets span out. Corner parcels, for instance, tend to reach a longer extent of surrounding street networks than middle parcels, all else equal. We test these three hypotheses in our case studies at Bugis, measuring the *surrounding floor area*, the *spacing*, and the *network reach* of a location in both study sites within a 200m network-based walking radius.

Surrounding Floor Area describes the total amount of gross floor area that is accessible around a location within a given walking radius. *Spacing* denotes the average distance between whole buildings within the given access range. It is found be dividing the total outdoor pedestrian network length (which can include multiple parallel paths) by the number of buildings. Our spacing measure therefore does not describe the true distances between adjacent buildings, but rather the length of pedestrian paths per building. *Network Reach* captures the cumulative total network length available to a pedestrian in a 200m-access radius around a place. The metric can distinguish between the indoor (circulation networks inside public buildings, malls) and outdoor extent of the pedestrian network around a place (sidewalks, pedestrian crossings, arcaded paths).

Beyond these three urban form variables, we are also interested in the spatial qualities of the areas' streets. We analyse seven characteristics of street edges that affect the experience of intensity via individual building frontages.

First of these seven characteristics, *Sheltered Walkways* describe the amount of outdoor network that is sheltered as opposed to exposed to an open sky. The cumulative sheltered network length is expressed as the percentage of covered paths among the total outdoor pedestrian network within a given 200m-walking radius.

Entrance Count captures the total number of outside doors that enter the streets within a given network radius. Building entrances work as both origins and destinations of pedestrian traffic on city streets – streets with more entrances, everything else being equal, tend to channel more people.

The *Ground-Floor Heights* capture the amount of buildings whose ground floors are at least four feet above or below the street level. We capture the ground-floor height metric as the percentage of building entrances accessible along the outdoor network above and below the assumed ground floor within a given 200m radius.

The *Setbacks* measure the average distance between building entrances and the nearest outdoor pedestrian path for all building entrances within a given radius. Buildings with wider setback, too, increase the effort for access and decrease the visibility for bypassers.

Age Diversity quantifies the age distribution of buildings within the same access radius. Variations in building age may contribute to the perceived intensity of urban spaces. To capture the variation between building ages, we group buildings into age groups that get shorter in time as group is nearer to the present (e.g. 1800–1900; 1990–1950; 1950–1975) and calculate age diversity as an entropy index (Limtankool et al., 2009). The index examines how uniformly building ages are distributed throughout the study sites. It is defined as:

$$E = -\sum_{i=1}^{L} z_i \cdot \ln(z_i) / \ln(L) \tag{2}$$

where *E* is the entropy index, *Zi* the ratio of buildings in a given age group to the total number of buildings in the area, ,and L is the number of age groups. *E* is constrained between 0 and 1. It is 0 if all buildings in the study area involve only one age group, and 1 if buildings are equally distributed among all age groups.

Edge Permeability captures the amount of non-structural walls on the ground floor facades within the buffer area. Permeable facades increase the visibility of the building contents, and increase the opportunities for interaction. Our perimeter permeability metric measures the proportion of non-structural facade length to the load-bearing facade length in the study area.

Finally, our *Transience* indicator captures the amount of mobile vendors that are found around a place. We capture the availability of mobile vendors by simply counting them around each site, in the same 200m walking radius as the rest of the metrics.

3. Bugis Case Studies

The Bugis district is located in the Rochor area of central Singapore. A high-density, relatively low-rise district, it has a diverse urban form made up of shop-houses, modest-sized malls, office towers and a few Housing Development Board (HDB) blocks. Our two case-study sites were chosen approximately 350 meters from the nearest MRT entrance – a quality whose difference could otherwise play an important role in affecting the density of commerce around the sites (Figure 1). One situated on the corner of the Albert Centre, the other near the northern end of Haji Lane, were chosen for their interesting differences in the surrounding urban form. The Haji Lane location illustrates a rather well preserved fabric of the 19th century shop-houses accompanied by a few modern commercial buildings. The Albert Street location used to house a similar shop-house fabric until the 1950s, but has since been entirely redeveloped with modern deep-floor-plate multi-story commercial structures. During the survey in the fall of 2012, researchers collected three layers of information on the sites: 1) the ground floor structural typology of buildings, 2) the distribution of economic establishments and mobile vendors, and 3) the outdoor and indoor pedestrian circulation networks that are accessible to the public. The data was digitized and entered into GIS for spatial analysis. For both sites shown in Figure 1, we analysed a 200-meter buffer around the marked origin points and computed the corresponding metrics. Table 1 presents the outcomes of these measurements.

The total *Reach* to establishments, including both stationary stores and mobile vendors is 50% higher around the Albert Centre (1015) than Haji Lane (673), suggesting an overall higher accessibility to destinations around the former location. In other words, the Albert Centre site has 50% higher intensity according to our metric. How do we explain this difference?

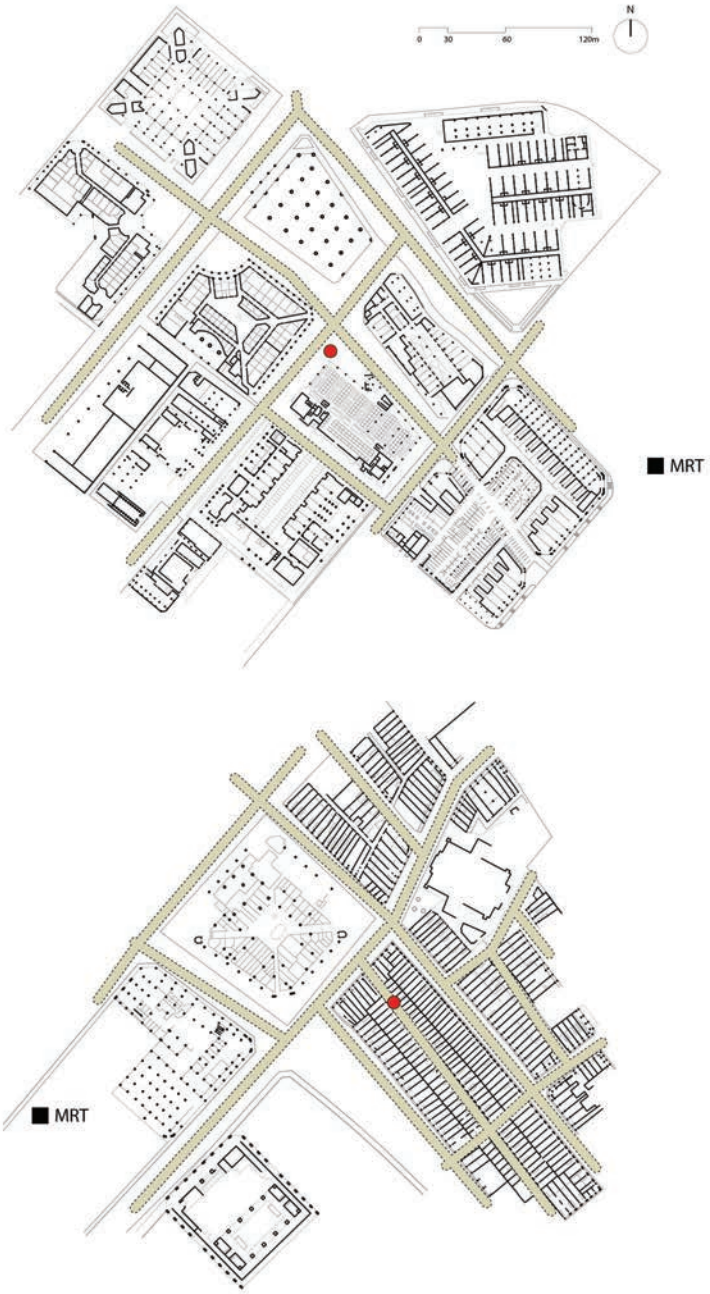

Figure 1. Case study areas. top: 200m buffer around the Albert Centre. bottom: 200m buffer around Haji Lane. The origin points of the study areas as marked with red dots.

Table 1. Results of case study area measurements.

Metric	Albert Centre	Haji Lane
Reach to commercial establishments	1015	673
Total floor area within a 200m range	603,000 m^2	181,500 m^2
Avg. Spacing between buildings	221.7m	21.5m
Network Reach	5,765m	6,127m
Sheltered outdoor walkways	2,408m	2,056m
Entrance count	230	380
Ground-floor heights (elevated)	11%	0.52%
Average Setback	4.2	2
Age Diversity	0.69	0.11
Edge Permeability	91.6%	77.8%
Transience	32	23

The 200m buffer around Haji Lane contains a slightly longer outdoor path network (6,127m) and significantly more individual buildings (285) than the Albert Centre. (26), so the difference in the accessibility to establishments cannot be attributed to a more connected street network or a denser spacing of buildings around Albert Centre. The difference is rather explained by the considerably larger commercial floor plates around the Albert Centre, which all together contain 333% more floor area than the area at Haji Lane. A number of large buildings, such as the Sim Lim Square, contain numerous small shops on up to six floors. Consistent with the fact that many of the establishments around Albert Centre are indoors, we also observe a greater number of doors on the streets around Haji Lane (380) than Albert Centre (230).

From the perspective of the ground floor morphology, the street edges around Haji Lane are more aligned with the ground plane than the street edges around the Albert Centre. We only observe 2 out of 380 street entrances around Haji Lane that are elevated above the ground floor. At the Albert Centre, in contrast, 27 of the 230 entrances are raised above ground. The higher total number of buildings around Haji Lane (285 versus 26) suggests that architectural variety is wider around Haji Lane. Buildings are much closer to each other at Haji Lane and setbacks smaller. But interestingly, this variety does not imply greater permeability of the street edges around Haji Lane nor a greater age diversity among its buildings. On the contrary, the edges of the larger buildings around Albert Centre, which are mostly designed with podiums around the ground floors, produce a higher percentage of permeable (non-structural) perimeter walls (91%) than the smaller and more numerous shop houses around Haji Lane (78%).

4. Discussion

Since both the Albert Centre and the Haji Land were deliberately chosen in the same Bugis commercial area and at roughly equal distances from the closest MRT entrance, we have been able to focus on how the morphological differences between both sites affect their differences in commercial accessibility.

The Albert Centre area has roughly 50% more commercial destinations in a 200m buffer than the Haji Lane area. This was explained by the considerably larger and newer structures around Albert Centre, which contain three times more commercial floor area. But, given the predominantly low-rise typology of the Haji Lane area, a surprisingly large number of commercial establishments were also found in a 200m buffer in its vicinity (673). If we look at the number of commercial establishments per each 1,000 square meters of surrounding floor area, the Haji Lane area actually supports more activities – 3.71 establishments per 1,000 square meters of surrounding floor area versus 1.68 establishments per 1,000 square meters of surrounding floor area at the Albert Centre. This difference could, in part, be due to the larger size of individual establishments around the Albert Centre.

The qualitative differences in urban form between the two areas are rather remarkable. Despite the fact that there is over three times more total floor area around Albert Centre, its buildings generate 65% fewer doors on the street than the buildings around Haji Lane, including back entrances, emergency exits, and service doors. The doors on the street play an important role in shaping the area's intensity. The differences in the amount of doors that the two sites produce are likely to be influenced by their contrasting building typologies – whereas the Albert Centre is surrounded by relatively large podium block structures, which contain elaborate public indoor circulation networks, the buildings around Haji Lane are small and utilize the street as their main circulation spine.

Overall, the comparison of the sites illustrates found that a high density of commercial accessibility can be achieved with remarkably different building types and neighborhood configurations. The methodology we use can be automated in such a way that it could investigate not only intensity related patterns, but also various other metrics, in different contexts within Singapore and beyond. It is too early to draw any causal inference about the efficacy of different urban design solutions from the study and more research is needed to understand the social and economic effects of urban form on both sites. But the development of urban form metrics that capture important qualitative aspects of places is an important step towards developing a better empirical understanding of how good urban environments work.

The research has so far explicitly focused on urban form, but not adequately on socio-economic activities, zoning laws, incentives, historical trends, or behavioural

patterns that may potentially have crucial impacts on the commercial intensity of the area. It would be interesting in follow-up research to gather ethnographic activity data on how the streets and public spaces between the buildings are being utilized on both sites, and to tie the behavioural evidence together with the spatial and economic patterns.

References

Anderson, S. (ed.): 1978, *On Streets*, MIT, Cambridge, MA.

Avent, R.: 2011, One Path to better Jobs: More Density in Cities. In *The Gated City*.

Aylward, M. G.: 1969, Towards a Theory for Describing and Designing Adaptability in the Built Environment, *Transactions of the Bartlett Society*, **7**, 129–147.

Bhat, C., Handy, S., Kockelman, K., Mahmassani, H., Chen, Q. and Weston, L.: 2000, *Development of an Urban Accessibility Index: Literature Review*, Research Report 7-4938-1, Centre for Transportation Research, The University of Texas at Austin.

Clemente, O., Ewing, R., Handy, S. and Brownson, R.: 2005, *Measuring Urban Design Qualities: An Illustrated Field Manual*. Princeton, NJ.

Ewing, R., Handy, S., Brownson, R. C., Clemente, O. and Winston, E.: 2006, Identifying and measuring urban design qualities related to walkability, *Journal of Physical Activity and Health*, **3**(Suppl 1), S223–S240.

Forsyth, A., Jacobson, J. and Thering, K.: 2010, Six Assessments of the Same Places: Comparing Views of Urban Design, *Journal of Urban Design*, **15**(1), 21–48.

Gehl, J.: 2010, *Cities for People*, 1st ed., Island Press.

Habraken, J. N.: 1999, *Supports*, Urban Press.

Hillier, B. and Hanson, J.: 1984, *The Social Logic of Space*, Cambridge University, Cambridge, UK.

Jacobs, A. B.: 1993, *Great streets*, MIT, Cambridge, MA.

Larice, M. A.: 2006, *Great neighborhoods: The livability and morphology of high density neighborhoods in urban North America*, PhD Dissertation, University of California, Berkeley.

Limtankool, N., Schwanen, T. and Dijst, M.: 2009, Developments in the Dutch Urban Systems on the basis of flows, *Regional Studies*, **43**(2), 179–196.

Porta, S., Latora, V., Wang, F., Strano, E., Cardillo, A., Scellato, S., Iacoviello, V. and Messora R.: 2009, Street centrality and densities of retail and services in Bologna, Italy, *Environment and Planning B: Planning and Design*, **36**(3), 450–465.

Salmon, F.: 2012, "Why jobs require cities". Available from: Reuters, Opinion <http://blogs.reuters.com/felix-salmon/2012/02/02/why-jobs-require-cities/> (accessed 6 March 2013).

Sevtsuk, A. and Mekonnen, M.: 2012, Urban network analysis: A new toolbox for ArcGIS, *Revue internationale de géomatique*, **2**, 287–305.

Sevtsuk, A.: 2010, Path and Place: A Study of Urban Geometry and Retail Activity in Cambridge and Somerville, MA, PhD Dissertation, MIT, Cambridge, MA.

Smithson, A. M. and Smithson, P.: 2005, *The charged void: urbanism*, Monacelli, New York.

Southworth, M.: 2003, Measuring the Liveable City, *Built Environment*, **29**(4), 343–354.

Talen, E. and Duany, A.: 2006a, Neighborhood Level Social Diversity, *Journal of the American Planning Association*, **72**(4), 431–446.

Talen, E. and Duany, A.: 2006b, Design That Enables Diversity: The complications of a planning ideal, *Journal of Planning Literature*, **20**(3), 233–249.

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RESOURCE DRIVEN URBAN METABOLISM

How can metabolic scaling affect urban design?

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Abstract. City scale projects are complex multivariable problems and have previously been addressed using a variety of organisational principles, whether it be the infrastructural grid, used by Ludwig Hilbersheimer in his project "Hochhausstadt" or the spinal organisation of the Tokyo Masterplan done by Kenzo Tange and the Metabolist Movement. This project strays from traditional methods of structuring a city and investigates a novel self-engineered anticipatory model, which focuses on the use of generative and genetic algorithms to develop a new associative system to develop coastal cities in arid climates. The system functions as a negative feedback loop, analysing existing conditions, and by a series of mathematical functions, projecting the new growth patterns for major components of a city, such as building envelopes, road networks, canal networks and public space distribution as a result of the cities internally generated resources.

Keywords. Computational design; generative & evolutionary design; tooling; city modelling; urban metabolism.

1. Introduction

An IPCC study indicates that desert climates are expanding (IPCC, 2007), which points to current problems of living in desert climates as being a pressing matter. This project tries to mitigate some of these immediate problems by proposing a new development model for Qatar, which has its high CO^2emissions (The National, 2011), high population growth of 12.6% per year (WolframAlpha, 2011) and very little to no

access to freshwater. There are no rivers or lakes, and the country has an annual rainfall below 75mm per year (Gaisma, 2012). The rainfall, and the small amount of surface water this creates, is almost the only access to freshwater for the population of Qatar, which has made them heavily dependent on the energy intense process of desalination since the 1950's for their freshwater needs (Al Mohannadi, 2010).

2. Precedents

Developing new design strategies for urban developments is not a new idea, and there are two specific projects that are beneficial to analyse in relation to their drivers for urban growth in order to describe how the methods utilized in this research project separates itself from its precedents.

In 1924 Ludwig Hilbersheimer proposed a theoretical project named "Hochhausstadt" (– "Skyscraper city") where the city is expressed as an infrastructural grid fitted with architectural program (Aureli, 2011, pp. 13-16). Having the grid as the underlying structure for the city makes the process of urbanization a predictable task, and the outcome very homogeneous. The project is seen as a first attempt to enable people to model and comprehend the complex relations, of an infinite city without the use of heavy computing, because of the modular logic that has been developed for the design proposal.

In 1960 Kenzo Tange proposed his theoretical plan for Tokyo, a plan where the city is organized linearly around a central axis (a road) from which secondary roads branch off (Lin, 2007). Even though the organization of Tange's plan differs from Hilbersheimer, the generated morphology is equally as predictable, quoting Peter Smithson:

> "Having a central axis of transport, from which all network originates, will require all vehicles to cross the central axis at some point on its way from point A to B, even though they have no business there." (Lin, 2007)

This reasoning suggests that people living in this city, would be more likely to live along the central axis in order to minimize their driving distance, and thereby create a long thin city.

The above examples indicate, that using traditional means of urban growth, such as infrastructure will create predictable urban morphologies. The intention of this project is to create a novel growth model, by using a resource-based driver for the generation of a city, where you cannot prescribe the resulting morphology.

3. Method

This section will first describe how metabolic scaling was used to dimension building envelopes and different networks of the city, then how genetic algorithms

were used to optimize the branching strategy for a canal network (elaborated in section 4.2).

3.1. METABOLIC SCALING

The city is an incredibly complex system made up of many different variables, both visible and invisible. When looking at cities as single living entities, they seem to posses a metabolism like the one inherent in all living systems.

> Biological metabolism functions through surfaces and branching networks, and there has been a century or more of research into the mathematical parameters common to all living forms. In cities too, the operation of metabolism occurs through urban surfaces and urban networks, and is a remarkable similarity between the mathematics of biological metabolism and urban metabolism. (Weinstock, 2011)

Bettencourt et al. describes, in the paper "Growth, Innovation, Scaling and the pace of life in cities" (Bettencourt et al., 2007), how urban- and metabolic systems have similarities, through a series of mathematical functions. However it is summarized that one power law function can determine the makeup and subsequent scaling of any network or mass sensitive system:

$$Y = Y_0(M^b) \tag{1}$$

Where Y is some observable characteristic, Y_0 is a constant related to that characteristic. M is the mass of the object in question, and b a multiple of ¼ (Brown and West, 2000). This formula was used to determine the footprint (Y) and height (M) for the building envelopes within the city proposals. Y_0, a constant relative to the footprint, was determined by using a "parent" building; where the height and footprint was known, so that it was possible to isolate Y_0 for further use. The parent building was used to test the theoretical concept, saying that a mouse mass is metabolically related that of an elephant, could also be applied to architecture.

Another formula was used to dimension other components of the city, which is presented in the paper: "*The fractal Lung: Universal and species related scaling patterns.*" The formula is as follows:

$$S_z = S_0(\alpha^z) \tag{2}$$

The formula doesn't take mass into consideration, but the depth of a given network. Using a tree as a model: S_z is the size of a branch at the "z" depth level (length or width). S_0 is the size of the trunk, and α^z is a constant where $\alpha < 1$. In

the case of most natural systems where α is about .75, interestingly complies with the rules for mass based scaling (Nelson et al., 1989). The use of this formula was very wide spread throughout the project, but was mainly used to define length and width of the canals and roads in the city. How this worked will be further elaborated in section 3.2, where the generative strategy for the canal network will be explained.

3.2. GENERATIVE AND GENETIC DESIGN

The main component of the project is a generative algorithm, meaning it is generating networks and entities over time (i.e. growth over time). Within the algorithm there are different sub systems that have individual rates of expansion, which will be controlled by an embedded control system (will be further elaborated in section 4.1) that will adjust the different growth rates to meet different criteria, for instance there will never be more people living in the city than it can sustain. Two of the sub systems have been genetically optimized, using a self-made genetic algorithm (Flake, 1998, pp. 339–360). The algorithm searches through a given morphospace (Goodwin, 1994, pp. 112–114) and evaluates the different outcomes based on a fitness formula.

To give an example, the city will have a canal network that branches out through the city (elaborated in section 4.1). The algorithm was developed based on the principles for L-systems and fractals (Flake, 1998, pp. 77–92).

The canal network has a few different parameters that can vary; the branching style (STL = short to long, or LTS = long to short), branching angle and meandering angle.

The branching style (STL or LTS) refers to the length of the different segments, which is defined by the metabolic scaling formula (2). Meaning if the first segment of canal (the trunk) is long then the following segments will get shorter (LTS), and vice versa if you start with a short(trunk) segment (STL).

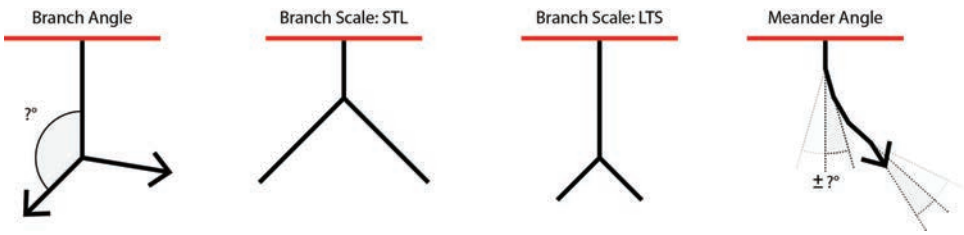

Figure 1. The different branching parameters.

The algorithm was designed to search for a optimal branching strategy for the canal network, the goal (fitness) for the algorithm was to create the network that would have the lowest value according to the fitness formula(3):

$$\text{Fitness Value} = \text{Length of network} / \text{total covered area} \quad (3)$$

It creates an initial population by stochastically arranging values from the parameters within the morphospace. More generations were created enabling or combining multiple parameters; this was to see the effect of varying different parameters. These initial populations are characterised as being the "gene pool", consisting of different parameter sets, i.e., morphospaces. This gene pool is then utilized for further genetic testing by cross breeding different individuals to see what would make viable solutions according to the fitness formula (3). Surprisingly the results from one of the initial populations where the effects of meandering were tested, not where cross breading was introduced, proved to be the fitter strategy. Bellow is an image of the fittest strategy and its associated values.

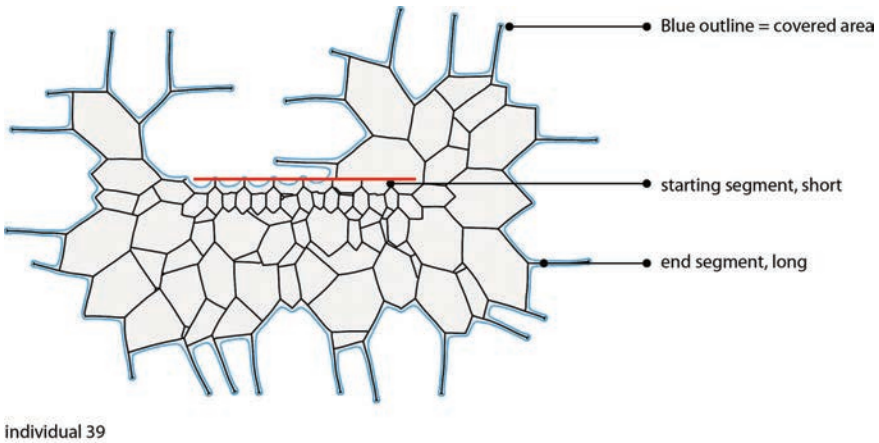

Figure 2. The fittest branching strategy and explanations of how data was derived.

Table 1. Data set for fittest branching strategy.

	Branching strategy	**Network length**	**Branching angle**	**Covered area**	**Meandering angle**
Figure 2	STL	115484,340	45/45	28257424,155	2

4. The Project

This section of the paper will describe some of the components that constitute the possible outcomes of the project, and how the city was enabled to grow as a result of a constant feedback loop between its internally generated resources and its current population. A city requires numerous different resources to sustain it self, however in order to test our proposed methodology, it was decided to focus on water; mitigating the issues of access and acquisition.

4.1. THE WATER STRATEGY

There will be a salt-water canal system dispersed throughout the city. The canals will be fitted with a special railing system that will function as a water productive surface, by being coated with a hydrophilic/hydrophobic polymer that was developed by a group of biomimicry researchers at the University of Sydney. The polymer will enable the system to withdraw water from the relative humidity in the air (Thickett et al., 2010a, 2010b).

The railing system along the canals will function as the foundation for the resource gathering within the project, but what if the system fails, needs maintenance, etc? If this happens the built in control system (part of the feedback loop) will take over by resolving to a secondary system that was developed along side the railing system. This other system is a series of easy to assemble and deployable floating solar stills that can be situated according to need, meaning if an area of the city is in desperate need of water, they will get a series of solar stills that can be hooked up to their local water network.

Figure 3. A section through a city, where a solar still, canals and roads are visible.

4.2. CITY COMPONENTS

As mentioned in the introduction to section 4, a city is composed of numerous different components, where the most important within this project is the water system. However of the multitude of different components of the project such as

Figure 4. The optimization process of the road network, from left to right: original, data sheet and adapted outcome.

roads, electrical and distribution networks, this section will focus on the development of the road network.

The road was developed using a generative algorithm that is loosely based on the concept of desiccation (mud-cracking), where the size and time to break is a derivative of the metabolic scaling formula (2). However the interesting aspect of the road design isn't how they where made, but how the size of the roads was evaluated and readjusted according to its projected traffic load. The intention of the roads was that they should be metabolically flexible, meaning they should have the possibility to resize to every metabolically scaled size. Using an A* evaluation algorithm enabled the roads to do so. The A* algorithm makes every node in a network, search for the shortest path to every other node in the network (excluding themselves), as a path is "crossed" it gets counted and at the end of the process, every node and path has an associated count. This crossing count data can be used to determine if a road is appropriately scaled or needs to be resized to fit its projected traffic load (see images below) (Hart et al., 1968).

5. Evaluation

In order to determine whether or not there are being made positive changes to the city as a system, there must be an evaluation in correlation to the earlier stated ambitions – to create a system that can generate cities over time as a result of its internally generated resources. Following will describe two different means of evaluation, one being the use of a fitness for the cities and how this was determined and used. The other evaluation method sampled different patches through out the city proposals, and compared them to patches from real cities of the region. The different types of evaluation served different purposes, the fitness evaluation was to indicate which system had the highest functionality. The comparative analysis was to analyse how close the generated outcomes would be to cities that had been developed over a long period of time, rather then what we see now where western ideals are being implemented in a middle-eastern context.

5.1. THE FITNESS FORMULA

The fitness of the cities was calculated based on a formula that utilized the values in the table below (the table represents values from two generated cities).

$$\text{Fitness} = (\text{length of water network} / \text{number of buildings}) / \text{combined connectivity of the road and water networks.} \quad (4)$$

Dividing the canal network length by the number of buildings, gives a ratio as to how much canal there is per building, thereby giving a value as to how well the system have dealt with the issue of water access. The combined connectedness of the two networks is calculated by the A* algorithm (described in section 4.2). This portion of the equation is preferential to low numbers meaning that the connectedness of the roads and canals are high. The formula favours cities with a high number for the building to canal ratio and a high connectivity. Below are two images of some of the generated cities.

Table 2. Table displaying gathered values that were used to calculate the fitness of the cities.

	Number of buildings	**Length of water canals (m)**	**Sustainable population**	**AVG connectivity water**	**AVG connectivity roads**
Low-rise city	14.880	233.351,812	764.489	5.745	5.694
Tent Pole City	7.391	150.853,117	494.213	9.206	5.206

Figure 5. (left) Low-rise – City with a fitness value of 1,370, and (right) Tent Pole City with a fitness value of 1,410.

5.2. COMPARATIVE ANALYSIS

It was chosen to take samples of 5 by 1 kilometre from three vernacular cities within Qatar's climactic region, which was thought to represent a wide variety of

city morphology. Within the big samples smaller samples were made that were analysed for smallest and largest footprint, number of neighbouring houses, number of courtyards, to name a few. The cities that were tested were Bandar E-Abbas in Iran, Jeddah in Saudi-Arabia and Baghdad in Iraq. The same type of test was conducted on the generated city proposals, one of which is displayed bellow. The proposal with the lowest deviation was the best in terms of creating the "image of a city".

Figure 6. The sample to the left is from Jeddah, Saudi-Arabia, the other samples are from a city proposal. See table 2 for deviation data.

Table 3. Deviation data for figure 6.

	Mean area deviation	**Built area deviation**	**Unbuilt area deviation**	**Built % deviation**	**Mean neighbouring deviation**	**Average deviation**
Figure 6	0,969	0,675	1,225	1,407	2	1,259

6. Conclusion

The experience that was gathered using the city-generating algorithm led to the conclusion that cities, as dynamic and difficult to understand as they are, can, to an extent, be grown and designed holistically. In the near future, when this kind of design challenge becomes more than a project experiment, it is imperative that some of the logics and methods that have been developed in this project should be elaborated and implemented for the use in real-world applications.

It was learned that it is possible to create a mathematical growth model that revolves around the resources of a city. In order to prevent over or under production of architecture, it is seen as a possibility to embed this new model into future urban plans and/or cities. This is not saying that architecture does not posses the ability to promote change; there is simply a need for a new development paradigm that meets the needs of a city, but does not over interpret them. The remaining question is; did

the project produce a new methodology for urban development? In short, yes. Though it is not complete, the project proposes some innovative approaches towards formalizing, developing and implementing a new methodology for the urban places of the future. This project proposes that a resource driven urban model is a definite possibility, and should be realized.

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References

Al Mohannadi, H.: 2010, *"Water Management in Qatar"*. Available from <http://www.wgpas-undp.org/index.php/en/national-capacity-needs-for-the-effective-joint-management-of-shared-water-resources-in-arab-states-7-9-june-2010-tunis> (accessed 27 Nov. 2012).

Aureli, P. V.: 2011, The Possibility of an Absolute Architecture. MIT, Cambridge, MA.

Bettencourt, L. M. A., Lobo, J., Helbing, D., Kuhnert, C. and West G. B.: 2007, *Growth, Innovation, Scaling, And The Pace Of Life In Cities*, *Proceedings Of The National Academy Of Sciences*, **104**(17), 7301–7306.

Brown, J. H. and West, G. B.: 2000, Scaling in Biology, Oxford University, New York.

Gaisma: 2012 "Weather data for Doha, Qatar". Available from <http://www.gaisma.com/en/location/doha-qa.html> (accessed 27 November 2012).

Flake, G. W.: 1998, *The Computational Beauty of Nature - Computer Explorations of Fractals, Chaos, Complex Systems, and Adaptation*, MIT, London.

Goodwin, B.: 1994, How the leopard changed its spots - The evolution of Complexity, Scribner, New York.

Hart, P. E., Nilson, N. J. and Bertram, R.: 1968, *A formal basis for the Heuristic Determination of minimum cost Path*, *IEE transactions of Systems, Science and Cybernetics*, **4**(2), 100–107.

IPCC: 2007, "IPCC fourth assessment report: climate change 2007". Available from <http://www.ipcc.ch/publications_and_data/ar4/wg1/en/faq-3-3.html> (accessed 27 November 2012).

Lin, Z.: 2007, *Urban structure for the expanding metropolis: Kenzo Tange's 1960 plan for Tokyo*, Journal of Architectural & Planning Research, **24**(2), 109–124.

Nelson, T. R., West, B. J. and Goldberger, A. L.: 1990, *The Fractal Lung: Universal and Species-related Scaling Patterns*, *Cellular and Molecular Life Sciences* **46**(3), 251–254.

The National: 2011, "Region's carbon emissions doubled in past 30 years: Report". Available from <http://www.thenational.ae/news/uae-news/environment/regions-carbon-emissions-doubled-in-past-30-years-report> (accessed 27 November 2012).

Thickett, S., Neto, C. and Harris, A.: 2010a, "*Can Mimicking Nature Quench Our Thirst?*" Available from <http://www.australasianscience.com.au/article/issue-may-2010/can-mimicking-nature-quench-our-thirst.html> (accessed 1 December 2012).

Thickett, S., Neto, C. and Harris, A.: 2010b, *Biomimetic Surface Coatings for Atmospheric Water Capture Prepared by Dewetting of Polymer Films*, *Advanced Materials*, **23**(34), 3718–3722.

Weinstock, M.: 2011, *The Metabolism of the City*, *Architectural Design Magazine*, **4**(1), 102–107.

Wolfram Alpha: 2011, "Data for Qatar". Available from <http://www.wolframalpha.com/input/?i=qatar> (accessed 7 September 2012).

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 571–580. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

DRAWING THE INVISIBLE: VISUALIZING PERSONAL SPACES

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Abstract. The present research discusses the importance of human activity as a place-making coordinate, and proposes the Activity Counter Maps (ACM) as a methodology for visualizing people's social spaces. Through two case studies, the ACM were tested for creating representations of both intensity of occupation in public spaces and people's public distances combined into a unified "three-dimensional public shape". The research analyses the resulted images and discusses its possible applications for digital design.

Keywords. Digital visualization; patterns of occupation; social spaces.

1. Introduction

The relationship between activity and space is a complex one. The built environment provides the scenario in which social and individual life takes place, and it's difficult to draw a clear division between when our activities dictates how our environment should be designed, and when our environment defines how our activities occur. Built space and activity permeate each other constantly, and while clear patterns and classifications can be observed in this relationship -from more flexible to more rigid correlations-, there is always a small degree of randomness in it (Hillier, 1988) making it difficult to visualize and study these correlations.

If place can be defined as human experienced space (Casey, 1997), the correlation between space and activity is crucial for understanding places. Place-theories are usually focused on issues like history, function, character and space, yet there is a lack of methodologies for studying the concrete spatial impact that we might have in a place by just being in it. Whyte (1980) already observed that by applying minor changes to the layout and elements of given public spaces can create major modifications in how people behave while being in them. In other words, one concrete space could change into many different places depending on

the way in which people stays in them. We could think that, if we are standing in a square which is crowded with people and in a matter of few minutes later people moves elsewhere, leaving the square almost empty, the square changes. What changes is not the space of the square or the personal spaces of the people that left, but what changes is the space of the place that the square is, explained by the fact that people generate spaces when interacting with each other. Edward T. Hall (1966) defines different degrees of individual distances for human beings, an "anthropological space" that is generated by us being in the space and in contact with others. These distances are invisible areas around us and they represent different degrees of contact with others. Hall describes four different distances: intimate distance, personal distance, social distance and public distance. One problem is that these distances are observed to exist, yet they are invisible for the human eye. They are rather a sense of space than a clear boundary.

In order to study these personal spaces and use them as a design coordinate, first we need to find a methodology for translating them into architectonic language: a clear figure-ground relationship showing the interactions between solid, boundary and void. For this, digital tools can be crucial. They can be used not only for creating new approaches and possibilities to the design process, but also for revisiting old problems from a new perspective. Digital representation and visualization can generate new ways of perceiving and understanding old yet valid and relevant concepts (Ware, 2004).

Today, architecture makes use of all sorts of visualization tools for improving or modifying the design process. We can visualize how a building will behave in terms of thermal performance, aerodynamic performance or acoustic performance, so we can modify our designs accordingly. The fact that we can turn this information into images is what makes this information meaningful for the design process: suddenly we can see how the wind "looks like", and moreover, how it looks like when encountering a projected building. Can we do the same for the personal spaces described by Hall? This paper introduces the Activity Counter Maps (Fujii, 1972) as a methodology for visualizing people's personal spaces interacting in public places.

2. Introduction to the Activity Counter Maps

The Activity Counter Maps (ACM) is a digital tool that allows representation and visualization of different kinds of data in a geographical context; combined with GIS, any database containing geographical locations could be translated into ACM. For instance, a database of all the tourist attractions in Tokyo, when translated into ACM, allowed an easy visualization of clusters of tourist activity (Kubota, 2006). What the ACM does is to assign an area of influence to an object

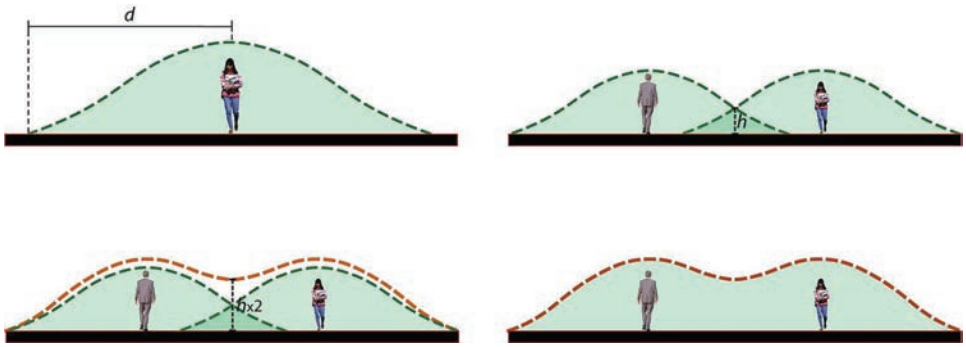

Figure 1. The logic behind the Activity Counter Maps.

or location in the space. The radius and height of the area of influence can be assigned accordingly to the specific needs of varied researches (Figure 1). When x areas of influence meet, the highest point where they are intersected is multiplied by x, generating a new common area of influence. The process goes on until every area of influence is combined with the others into a resultant common area, allowing visualization of both the shape of the combined personal spaces and the intensity of activity, since the combined spaces grown vertically. Therefore, the intensity of activity can be expressed three-dimensionally, just like topographic contour lines. Especially for this research, here is where it lays the potential of this tool; it can be used not only for generating graphics, but also to generate form, and therefore, space.

3. Case Studies: Introduction to Ueno Park

For the first case study, we decided to test form-generation capabilities of the ACM in Ueno Park (Ueno Onshi Kōen, 上野恩賜公園). Ueno Park is located in Taitō ward, to the northeast of the Imperial palace (Figure 2). It is the first public park in Tokyo and the most popular one in terms of number of visitors. The main reason why we decided to carry out the case study in a park was because it allowed us to study people interacting with an undemanding and flexible environment, in which the location, duration and range of activities carried out by the visitors were more related to personal choice rather than the constrains and limitation of a fully shaped urban environment.

Among Tokyo's parks, Ueno stands out due to its location, history and character. It has been related to leisure activities since the Kanbun era (1661–73), it was the site for one of the most important battle of the Boshin war (Battle of Ueno, 1868) and it has serve as evacuation area during natural disasters and WWII

Figure 2. Ueno Park: final subdivision into 33 sub-places.

bombings. Today, Ueno Park is a cultural spot in Tokyo, containing temples, museums, and theatres. Despite the dramatic and numerous changes occurring in the city since the Meiji period, the outline of Ueno Park has barely changed. Instead, the park is filled with areas and places which belong to different historical periods and events. This gives the impression of a park made up from different patches, apparently disconnected from each other, yet the park has managed to retain integrity as a place, and this integrity is greatly given by the visitors and the way in which they occupy the park. Therefore, for the first case study, we wanted to visualize the intensity and patterns of this occupation.

4. First Case Study: Intensity of Activity in Ueno Park

For this research, we defined intensity of occupation as the spatial relationship between density of occupation and the boundaries of the occupied places: a spatial

visualization of density. The first requirement for this visualization was quantitative information about the number of people visiting the park. Regarding people's flow in Ueno Park, not up-to-date data was available, so we were in need to collect our own. First, we focused on finding available data from many public facilities of the park (Museums, Zoo, theatres). We compared the monthly number of visitors per facility during two years (2006–2007). These facilities combined received more than twelve millions visitors per year. We could observe that there was clear correlation between years in terms of the total number of visitors per month. However, there was no such correlation when doing the same comparison for each individual facility; their monthly numbers of visitors vary drastically from one year to another. The only facility in which we could observe a correlation between years was Ueno zoo, which is also the only open-air facility in the park. Interestingly, there was a clear monthly correlation between the sum of all the visitors and the visitors of the Zoo. This suggested the most of the people coming to the museums were also considering spending some time in the park. Nevertheless, this did not clarify the amount or flow of people in the open area of the park.

4.1. FIRST CASE STUDY: COUNTING OF PEOPLE

In order to visualize the intensity of activity in the park, we needed to perform our own counting of people. For doing so, we divided the park into sub-places. This required a consistent methodology for identifying the boundaries of each sub-place, so we decided to use Lynch's "image of the city" methodology (1960). Ueno Park has a strong "urban character"; it appears as a portion of the city where the buildings have been replaced with trees, so regardless that Lynch's methodology was first intended to be used in fully urban environments, it adapted to Ueno Park with ease. We started the subdivision of the park with only one rule: no sub-places could be fully contained by another one. This resulted in a network of 33 sub-places of similar size, and manageable for a person to count the people inside them (Figure 2).

The counting was performed during one single day, simultaneously in each one of the 33 sub-places. We decided that the counting would be done from 10:00AM to 17:00PM, since in previous research we registered that before 10:00AM the level of activity was not significant, and after 17:00PM, the level of activity started to decrease significantly in accordance to the same period of time in which most of facilities in the park are open to the public. Another requirement was that the day in which the counting would be executed had to be a weekday, because during weekends the park is visited by great numbers of people, making the counting more difficult and potentially less accurate.

The counting was carried out as planned. We collected samples of ten minutes per every hour. This time periods for counting people occupying public spaces

have been proven consistent in providing reliable samples, especially for data extrapolation (Gehl et al, 2006). During the ten minutes samples we counted everybody who was inside the boundaries of a given sub-place, regardless of their age, gender or activity. The volunteers who performed the counting were encouraged to do their best not to recount an individual during a single sample, but if an individual could be found staying in a place during more than one sample, he had to be included in it. In other words, everybody being in a place during the counting time has to be counted, regardless if they were there during previous samples.

4.2. FIRST CASE STUDY: GRAPHICS GENERATION

Prior to the generation of the ACM, we needed to place the counted people in each one of the 33 sub-places of the park. Using a simple script, the numbers of people were randomly yet evenly distributed in each sub-place, and each individual was represented by a dot (Figure 3). The randomness of the individual locations is consistent with the research, since what we want to visualize is intensity of occupation, not precise traffic flow.

Once the people were distributed we assigned them different areas of influence and tested different parameters searching for a single shape in the visualization results. The criteria for visualization was based on obtaining a clear distinction of the intensity of activity for each sub-place and, at the same time, a unified shape

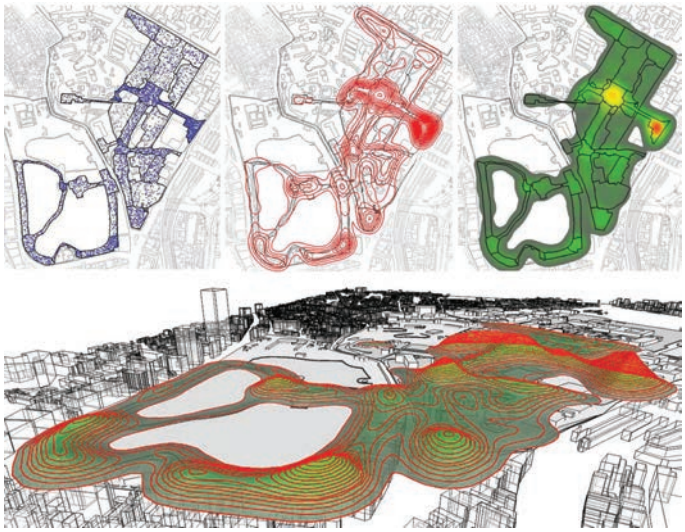

Figure 3. Sequence of graphic generation: from people distribution to 3D model of the ACM.

for the total of the park. The resulted images were obtained by assigning a radius of 30 meters to the area of influence of each individual. Using these parameters we obtained a total, unified contour in which was also possible to distinguish the particular activity for each sub-place (Figure 3), showing how the occupation for each sub-place merged with the others into a continuous, coherent shape.

Based on the obtained maps, it was also possible to generate colour-graduation graphics (Figure 3). When looking at the resultant ACM, sometimes could be difficult to visualize the boundaries of the sub-places in relationship their intensity of occupation. This was quite notorious when subplaces showed the combination of having a small size yet high levels of activity. In those cases, the graduation graphics allowed better visualization, showing the intensity of activity in a more general way, in which the sub-places where clearly identifiable.

The ACM made it easy to visualize patterns regarding the intensity of occupation in the park. During the studied day, it was possible to see a clear axis of activity made by sub-places 12, 15 and 16. The places with less activity were also the ones which are independent from the network of the park (sub-places 8 and 12), but the people visiting this places had the aim of doing so, since they are not part of any route. Most of the places shared the tendency showed by the main nodes (when the nodes increased or decreased their intensity of activity, the same happened in most places of the park). However, this changed during the fifth time span (14:00–13:00), when the places around Shinobazu pond started to show different tendencies than the rest of the park, especially by the end of the day, This shows an interesting correlation between special features and occupation: the clear spatial differences between the pond and the rest of the park also exist in terms of activity.

5. Second Case Study: Visualizing Personal Spaces

For the second case study, we decided to use the ACM for visualizing people's personal spaces while being in a public place. The research was focused in two of the sub-places of Ueno Park. They were chosen because their similarities in terms of size, shape and the amount and nature of the activities happening in them, which allowed us to record their activities using the same methodology. At the same time, their differences in term of location, surroundings and arrangement of elements offered the potential for interesting comparisons in the resulting maps. We decided to record one of the most essential and basic place-making activity: to stay. To voluntary taking place somewhere involves a conscious decision, and it offers a starting point for a wide range of various optional and social activities to appear.

For the data collection we filmed a series of videos on both sub-places. We filmed two days per place, one day on a weekend and another during the week, making sure that the weather conditions were similar in every filming session, and

no extraordinary events (parades, flea markets, etc.) were happening in the park during filming time. For each place, we filmed five minutes videos every thirty minutes, from 10:00AM to 19:00PM, giving a total of 16 videos per day. Two days per place resulted in thirty-two videos per place, sixty-four in total.

5.1. SECOND CASE STUDY: GRAPHICS GENERATION

After the video recordings, the next step was to translate the videos into digital drawings. While watching the footage we marked the location of every individual who decided to stay or were staying in the studied places during the filming times. The result of this process was sixty-four DWG files, each one containing the number and location of the visitors.

Based on the information in the DWG files, we could generate the ACM. While in the first case study the radius of the areas of influence assigned to the visitors was fixed to 30 meters for visualization purposes, for this case study the aim was to visualize the public distances of the visitors interacting with each other. Therefore, we assigned an area of influence according to the public distance of 7.6 meters, as described by Hall (1966), resulting in 64 images showing "snapshots" of combined personal spaces (Figure 4)

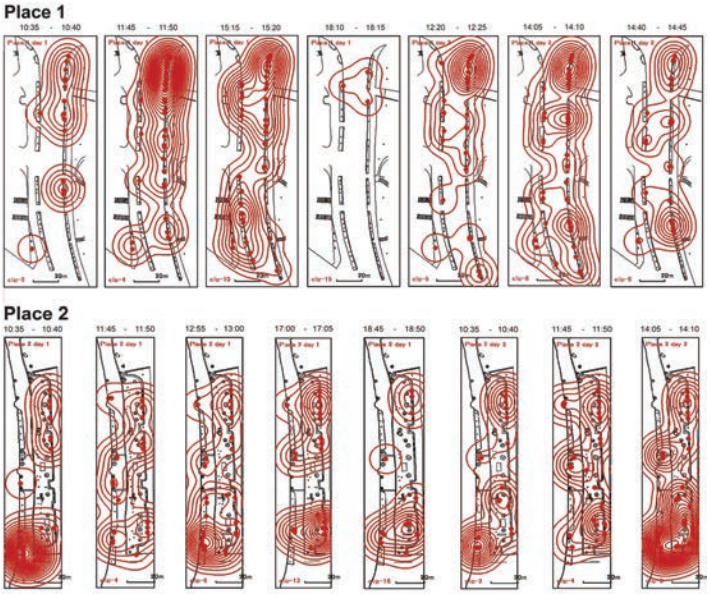

Figure 4. Sample results of people's personal spaces in the studied places.

Once the personal spaces became visible, interesting observations could be made. For instance, in place one a continuous curb alongside the trees was the only element where people decided to stay, and when the number of visitors was high, it was possible to observe an interesting coherency between the layout of the place and the personal spaces. A different situation occurred when only a few people decided to stay. The locations where people chose staying were neither too closes nor too far from other people: most of the time they chose a location inside the public distance of another person and we rarely observed someone isolated from the rest of the people staying in the place. The combination of these personal spaces generated very symmetrical shapes, which could be seen repeatedly during early morning and late afternoon. In place one, the shapes of the combined personal spaces were very regular. We could observe a different situation in place two, where most of the elements that shaped the place seemed randomly scattered along the place with no apparent consistency and some of the spots where people decided to stay rarely repeated during the day. This created irregular and unpredictable combinations of personal spaces: people stayed in random spots, sometimes seating on a curb, or sometimes under a tree. This generated a separation between the shape of the place and the shapes generated by the personal spaces, giving the impression of being independent from each other, evincing a separation between place and activity.

6. Conclusions and Future Development

By comparing the two studied places, it could be observed that the correlation between personal spaces and the space defining elements was an indicator of the level of integrity between a place and its inhabitants. This tells us about the deep integration between places and the way we occupy them. Especially in public spaces, activity becomes an important component in the overall perception of how a place finally is. In other words, spaces could be studied separated from the activity which occurs in them, but when we study the places which those very same spaces are, the activity has to be considered in relation to both space and character of that place. Both case studies showed that the ACM is a consistent tool for representing, visualizing and finally perceiving this place-activity relationship, translating quantitative data into qualitative images. However, there is plenty of space for improvements. Currently, the tool does have some arbitrariness to it. For instance, the ACM assigned a circular area to the counted people, but our perception of the space does not happen simultaneously in every direction. These personal spaces interact not only with each other, but also with solid and statics elements (architecture) which allow different levels of perception. Future developments of the methodology are planned to pursue improvements concerning

these two issues, getting closer to the aim of using the visualization of people's personal spaces as design parameter.

References

Casey, E. S.: 1997, *The Fate of Place: A Philosophical History*, University of California Press.

Fujii, A. (藤井 明): 1972, Theory of Counter Maps: Geometric Features of a Jordan Curve (活動等高線論：閉曲線図形の幾何学的諸特性について), Doctoral thesis, University of Tokyo, Tokyo.

Gehl, J., Gemzoe, L., Kirknaes, S. and Ekland, B.: 2006, *New City life*, The Danish Architectural, Copenhagen.

Hall, E. T.: 1966, *The Hidden Dimension*, Lowe & Brydone, London.

Hillier, B. and Hanson, J.: 1988, The Social Logic of Space, Cambridge University, Cambridge.

Kubota, A. (久保田愛): 2006, Sightseeing points of Tokyo (東京の名所図会), Master Thesis. University of Tokyo, Tokyo.

Lynch, K.: 1960, *The Image of the City*, MIT, Cambridge, MA.

Ware, C.: 2004, *Information Visualization: Perception for Design*, Morgan Kaufmann, San Francisco.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 581–589. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

VISUAL ANALYSIS OF THE RELATION BETWEEN CONCENTRATED DISTRICTS OF KNOWLEDGE-BASED INDUSTRIES AND THIRD PLACES IN OSAKA CITY

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Abstract. Recently, as the changes in the economic structure, service industries have become an important factor of the urban regeneration. Especially, Knowledge-based industry is garnering attention as an engine of urban economics. Urban present condition such as location of Knowledge-based industry visualization and analysis are main issues for people as well as policymakers, urban planner and designers. This paper presents analysis of the spatial characteristics of the distribution and spatial concentration of Knowledge-based Industry, specifically Business-support Services. Furthermore, this paper is intended to describe examination of the visual relation between spatial conditions and configuration by visualization using GIS and space syntax analysis. This paper shows that business support services are likely to concentrate in specific places. Results of this study show that each type of business support services is concentrated in different districts. Results show that creative design industries are located near the park, riverfront, and such third places with high integration and connectivity with the street by space syntax analysis. Results show that concentrated districts of creative design companies at inner block show relatively high local integration values and connectivity. This study elucidates how industrial concentration and spatial configuration can be ascertained visually.

Keywords. Spatial analysis; knowledge-based industry; third place; GIS; space syntax.

1. Introduction

As the economy grows, service industries have become an important part of the urban economy. Concomitantly with changes of industrial structure, the location of knowledge-based industry is garnering attention as an engine of urban regeneration. Knowledge-based industry is based on high technology or a highly skilled workforce in service industries. Therefore, human capital is the main factor

supporting knowledge-based industries. It is necessary to examine the distribution and spatial characteristics of knowledge-based industry where they are concentrated.

According to Richard Florida in The Rise of the Creative Class, creative capital based on human capital and urban-regional growth demonstrate that people, not businesses, are the engine of regional economic growth. Florida defines a 'Creative Class' as a group of well-educated people who have technical knowledge or specialty or artistic talents. Florida argues that they have similar tastes, a tolerant attitude and similar life styles. They also have needs for a sense of place, cultural diversity, amenities, activities of recreation, and such (Florida, 2002).

Oldenburg in The Great Good Place explains a third place that is not work and home and defines that third places are informal gathering places in which people gather, neither at home nor at work. Oldenburg explains the third places provide a place to connect with people in communities as well as a place to exchange ideas and news (Oldenburg, 1999).

In other words, to attract knowledge-based industry, these imply that we need human capital and a place to attract creative class. For this reason, a place-exploration based on spatial characteristics and visualization of urban present conditions is the main issue for urban policymakers and urban designers in urban planning and regeneration. As described herein, we regard the Knowledge-based industry to business support services, specifically so-called creative design (Economic Affairs Bureau, 2012), as a group of the creative class to elucidate characteristics and the relation of the concentrated districts and the third places by space syntax analysis. This study is an effort at visual analysis to ascertain the relation between concentrated districts of business support services and third places. Results suggest a visual methodology of integration analysis. Furthermore, visualized spatial information portraying the present urban industrial condition and spatial information can be provided.

2. Definition of the Knowledge-Based Industry and Creative Design Industry

2.1. KNOWLEDGE-BASED INDUSTRY

Knowledge-based industries are defined as described herein.

- Corporations that perform technology-based activities and which produce high-technology goods and services.
- A corporation that has a highly skilled workforce and which provides technical or highly skilled services such as finance, insurance and communications.

2.2. CREATIVE DESIGN INDUSTRY

This paper defines creative design industry, which is adopted as a "New Growth Strategy" of Japan, which are fashion, content, design, food, culture related industries. This study adopts a business-supported services system according as a Japan Standard Industrial Classification.

3. Spatial Scope and Overview of the Central Three Wards

For this study, we conducted a survey of a targeted area of central Osaka City: Kita Ward, Chuo Ward, and Nishi Ward. Table 1 and Figure 1 present an overview of the target area.

Table 1. Data characterizing the three wards.

Classification	Kita Ward	Chuo Ward	Nishi Ward
Area	10.33 km^2	8.88 km^2	5.20 km^2
Household	67,199	44,462	48,563 (2012.1.1)
Population	113,135	78,446	85,278 (2012.1.1)
Population density	10,952 people/km^2	8.836 people/km^2	16,400 people/km^2
Main facilities	Osaka Station, Nakanoshima	OBP	Utsubo Park

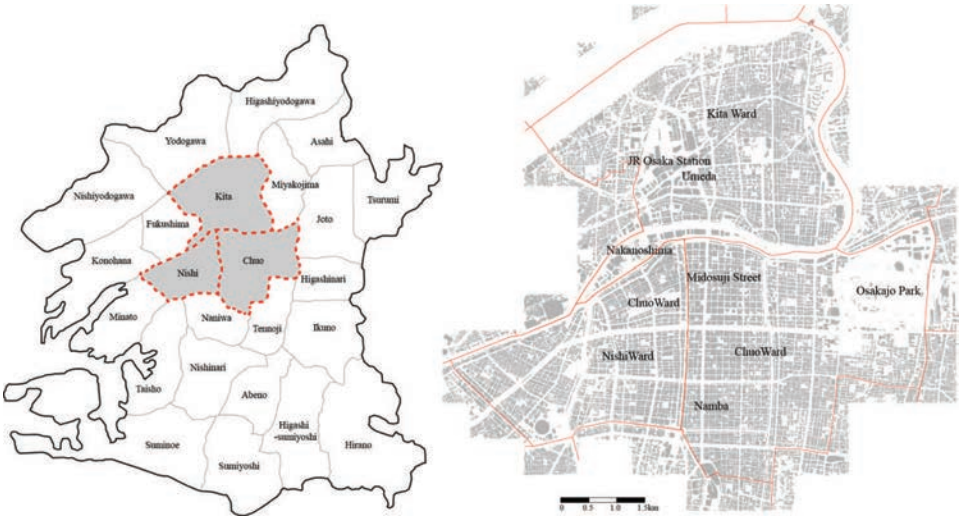

Figure 1. Osaka City: Gray Area shows the Spatial Scope of this study area.

4. Method of Analysis

This paper proceeds as follows. We start by defining and classifying business support services, specifically creative design industry. Furthermore, we explore concentrated districts of the creative design industry and analyze their spatial characteristics. We also analyze visual relations between the clusters and third places using GIS and Space syntax analysis.

4.1. CLASSIFICATION OF BUSINESS SUPPORT SERVICES

This paper divides service industries into three categories, as shown in Figure 2 below: business support services, life support services, and public services. Such a classification is done according to criteria we constructed on datasets which are ICT industry, professional, advertising, and other technical services such as finances, management consulting, and law.

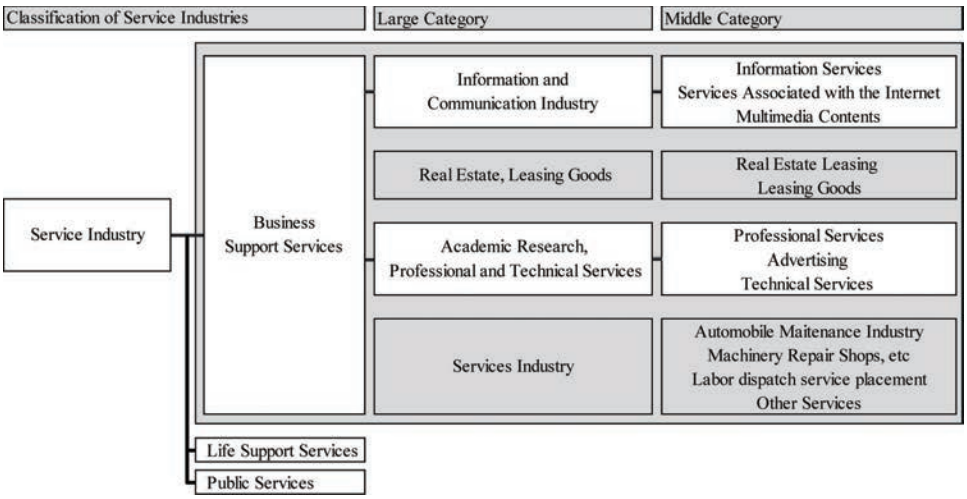

Figure 2. Classification of Business Support Services: Grey Highlighted Areas show the Scope of this Study.

4.2. DATA COLLECTION

We extracted corporate information and address data of business support industry companies from TSR Information in 1980, Chamber of Commerce and Industry in 1990 and 2000. Present condition data were extracted from the web site of the Osaka Chamber of Commerce and NTT i-Town page. In addition, data for third

places such as cafés, bars, restaurants, and galleries were extracted from the NTT i-Town Page.

4.3. PROCESS OF ANALYSIS AND VISUALIZATION

The analysis has proceeded in three stages:

1. Visualization of the geographic distribution of creative design industry businesses such as architectural design and graphic design in present data (Figure 3).
2. Exploration and visualization of the concentrated districts, and density analysis of the creative design industry (Figures 4 and 5).
3. Visual relation between concentrated districts of creative design industry and the third places using space syntax (Figures 6 and 7).

5. Spatial Analysis

5.1. VISUALIZATION OF DISTRIBUTION BUSINESS SERVICE INDUSTRY

We performed density analysis using GIS to find distribution of the business service industries and present conditions of concentration. The analysis results are presented in Figure 3.

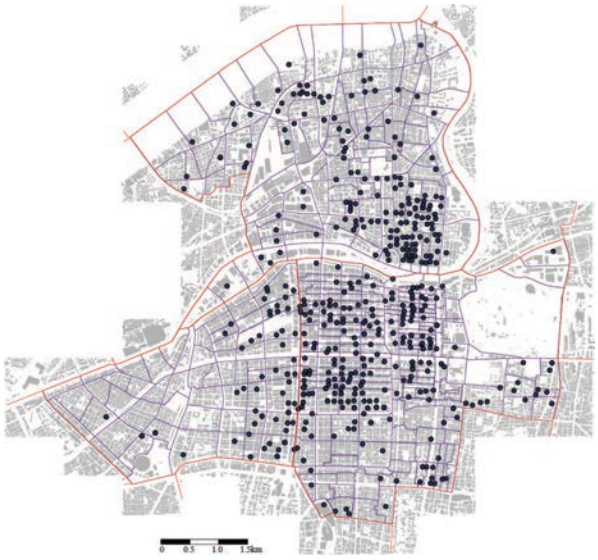

Figure 3. Visualization of distribution of creative design industry and concentrated creative districts.

5.2. EXPLORATION OF CONCENTRATED DISTRICTS OF CREATIVE DESIGN INDUSTRY

We performed density analysis using GIS to find concentrated districts of the creative design industries. Analysis results are shown in Figures 4 and 5. For example, in Kita Ward, most creative design companies are located at Tenma area near the riverfront. They are concentrated around Utsubo Park at Nishi Ward.

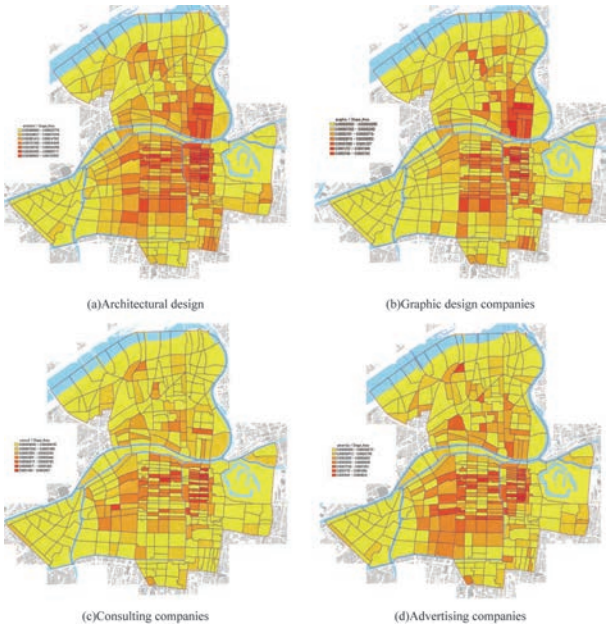

Figure 4. Visualization of concentrated districts of each type of business service.

Figure 5. Kernel Density Analysis of the Business Services in Osaka City.

5.3. AXIAL MAP ANALYSIS AND RELATION BETWEEN CONCENTRATED DISTRICTS OF CREATIVE DESIGN INDUSTRY AND THIRD PLACES

The axial map shows a network of intersection of the axial lines represented by the longest line of sight, which is useful to characterize every street segment. Two syntax measures used were Integration and Connectivity in this paper (Figure 6).

Figure 6. Axial map analysis of Osaka City: Axial lines in the map, where thick lines represent highly integrated street segments and thin lines represent segregated street segments.

6. Results

Results presented in this paper point to important implications for revitalization of urban design. The results are as follows:

1. Spatial analysis shows that knowledge-based industries are likely to locate specific districts with different types of business classification.
2. Results show that Creative design clusters are likely to be located near the park, riverfront, and such areas. Creative design clusters were formed within a block or one or two blocks distant from main streets or between main streets. However, a high integration value and connectivity prevail in spite of the location.

3. Findings from space syntax analysis show that both the business services clusters and the third places have high integration values and connectivity. Furthermore, both have a positive correlation between integration values and connectivity. Results show that the streets near the park or riverfront at inner block in the concentrated districts of creative design companies show highly local integration values and connectivity from the results of local axial analysis (see Figure 7).

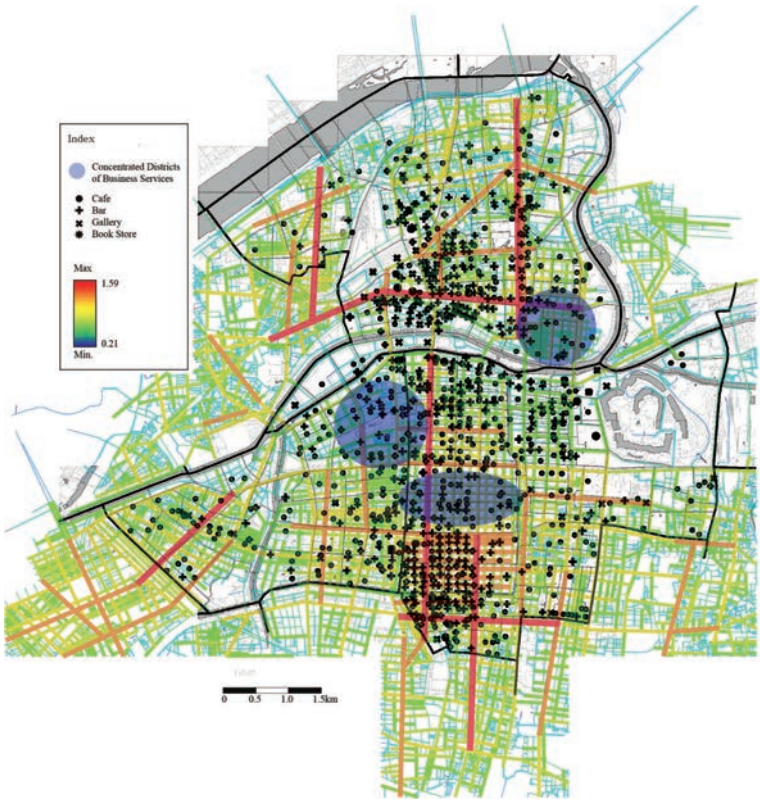

Figure 7. Overlap analysis of axial map analysis and third places: Map showing the relation between concentrated districts and third places.

7. Conclusion and Future Work

Accessibility for integrated urban information is a main factor for participation in urban design. Furthermore, the visualized analysis of a present condition is an important component for urban information. However, it is difficult for people to

follow-up urban conditions and information because of insufficient integrated and visualized information. From this paper, we were able to provide visualized information of those spatial characteristics, the relation between clusters and the third places, and their connectivity. These results show locations of attractive places and conditions of concentration in the CBD for knowledge-based industry.

These spatial characteristics can attract similar business services and third places such as cafés, bars, and cultural facilities such as galleries. This attractiveness enhances the reputation of the place, promotes the concentration of other business support services, and plays a role in fuelling place innovation.

Finally, we anticipate visualized information linked to the Google Earth showing results presented in this paper, and hope that it will encourage people such as policymakers, urban designers, and people searching for attractive places to participate in integrated urban design, and that it will help businesses to find optimal locations. These imply feasible open systems for the public in urban regeneration.

References

Economic Affairs Bureau, O. C.: 2012, the Outline of Osaka Economy, Osaka City, 131.

Florida, R.: 2002, *The Rise of the Creative Class: And How It's Transforming Work, Leisure, Community, and Everyday Life*, Basic Books, New York.

Oldenburg, R.: 1999, *The Great Good Place: Cafes, Coffee Shops, Bookstores, Bars, Hair Salons, and Other Hangouts at the Heart of a Community*, 2nd ed., Marlowe and Company, New York.

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MODELLING INFORMAL SETTLEMENTS USING A HYBRID AUTOMATA APPROACH

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Abstract. Automata based modeling of urban environments focuses on the bottom up emergence of particular phenomena through interactions at the disaggregated level. Two popular approaches are *cellular automata* (CA) for modelling fixed automata and *agent based modelling* (ABM) for modelling mobile automata. However, certain urban phenomena cannot easily be modelled by either CA or ABM alone. This research focuses on one such phenomenon, referred to as *leapfrog development*, which is a discontinuous and dispersed type of urban growth. A hybrid automata model is proposed for modelling such phenomena that combines both CA and ABM into a single integrated model. The proposed model is demonstrated by applying it to a case-study in Dhaka city for simulating the growth of informal settlements associated with the readymade garment industry.

Keywords. Hybrid automata; GIS; agent based systems; cellular automata; informal settlements.

1. Introduction

Automata-based modelling of urban environments is a dynamic, bottom up, and disaggregated approach to modelling (Longley, 2005). Automata are the components within the model that process information and change the state of the system based on a set of transition rules (De Smith et al., 2007). Benenson and Torrens (2004) has formulated the automata as

$$\mathbf{A}= \{\mathbf{S},\mathbf{T}\};\ \mathbf{S}= \{S_1, S_2, S_3, ..., S_n\};\ \mathbf{T}: \{S_t, I_t\} \rightarrow S_{t+1}, \quad (1)$$

where T is the set of transition rules, S_t is the state of the automaton at t time, I_t is the input information derived from neighboring automata, and S_{t+1} is the state of the automata process at time t+1.

Automata may be either fixed (such as a land parcel) or mobile (such as a pedestrian) (Benenson and Torrens, 2004; Batty, 2007). Two popular approaches

to automata based modelling are cellular automata (CA) for fixed types of automata and agent based modelling (ABM) for mobile types of automata.

This research focuses on the modelling of the growth of the informal settlements within cities. Both CA and ABM models have been used for modelling this type of growth. Sietchiping (2004) and Hill and Lindner (2010) have developed CA models, while Barros (2004) and Vincent (2009) have developed ABM models. However, there is evidence that certain discontinuous and dispersed types of urban development, called *leapfrog development*, play a significant role in informal settlement growth. The concept of leapfrog development emerged from studies on the spatial evolution of urban areas (Benguigui et al., 2001). This type of development is by definition influenced by both local and global dynamic factors. For example, industries providing particular types of job opportunities may concentrate in certain areas of a city and influence the 'leapfrog' growth of informal settlement by pulling low-paid migrants worker away from outside of cities. Through this 'leapfrogging', informal settlements develop at specific locations within the city that are close to work locations and where there is favourable land in combination with other informal mechanisms.

Modelling using either CA or ABM alone cannot easily capture the dynamics of such leapfrog development since both fixed and mobile automata need to be considered. From an urban modelling perspective, there is little research that investigates both the local (at the settlement level) and global (on a city scale) pattern of such leapfrog type informal settlement growth. For such types of growth, it is argued that a hybrid model is required that combines CA and ABM.

In the field of urban or city modelling, the 'hybrid' term has been used at two levels. At one level, there have been attempts to integrate micro/meso scale models with macro-level models, where micro/meso scale models are provided as modular components for simulating various urban local dynamics (Torrens, 2001). At another level, the idea of 'hybrid' models have been seen as integrating fixed and mobile units of cities (Torrens and Nara, 2007; Wu and Silva, 2009). However, these hybrid approaches appeared to be insufficient as they do not fully integrate CA and ABM approaches into a single model.

The aim of this paper is to propose a hybrid automata model where both CA and ABM approaches are tightly coupled in order to be able to model leapfrog type informal settlement growth. The proposed hybrid model is applied to a case study in Dhaka, the capital city of Bangladesh.

2. Case Study

Rural to urban migration has been the dominant component of urban population growth (Islam 2006a; Alam and Rabbani 2007). The readymade garment (RMG) industry in Dhaka makes a significant contribution to the country's economic

development, and the factories that have proliferated throughout the city have created a strong 'pull factor' for internal migration (Hoque et al., 2007). An estimated 300,000–400,000 migrants, mostly poor, arrive at the city annually (Rashid, 2009; World Bank, 2007). The workers in the RMG factories mostly come from this pool of migrants (Islam, 2006b; Mottaleb and Sonobe, 2011).

Despite the socio-economic importance of the RMG industry, the settlement issues of the factory workers have not been resolved, and as a result most workers will end up living in informal settlements. These settlements consist mainly of residential units made of fragile (kutcha) structure with one floor.

Unlike in other cities where informal settlements mainly develop at the urban periphery (Barros, 2004; Sietchiping, 2004), in Dhaka informal settlements have typically emerged within the city itself (Masum, 2009). Topological relations exist between informal settlement clusters and factory clusters. Figure 1 shows scattered pattern of informal settlements and factories.

The locations of the RMG factories strongly influence the location and pattern of the informal settlements. A reverse relationship can also be identified, whereby

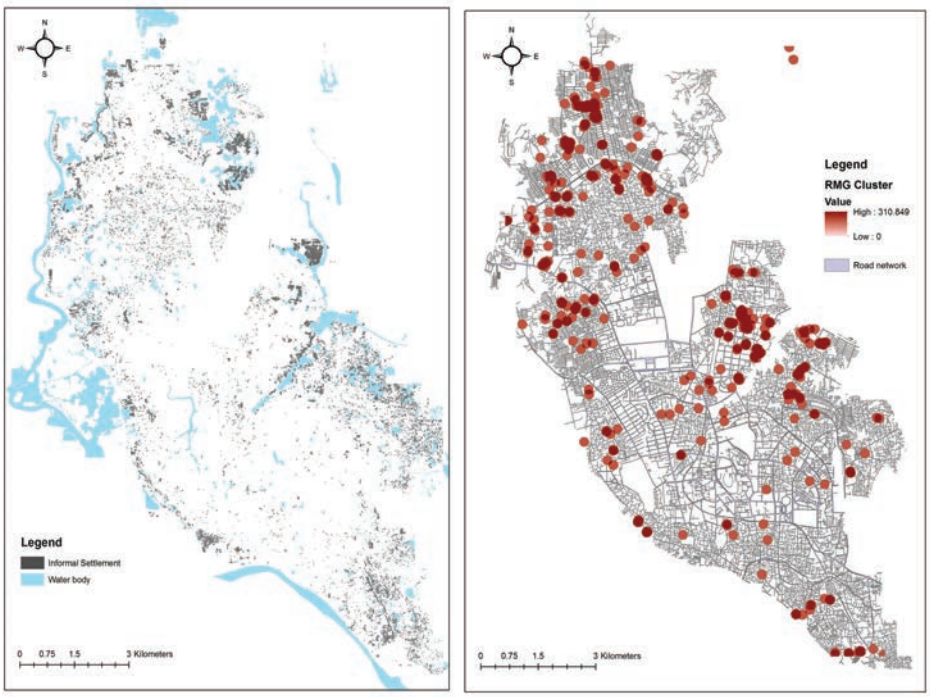

Figure 1. Scattered pattern of IS and RMG factories (black circle is industrial zone).

the location choice of factories is influenced by the locations of the informal settlements. In addition, Hoque et al. (2007) have found that most of the factories have been established besides main arterial roads and in buildings designed for other uses such as residential or commercial buildings.

2.1. HYPOTHESIS AND PROPOSED MODEL

Whenever there is a clustering of *RMG* factories, a clustering of informal settlements will also emerge. This clustering confluence leads to the development of non-homogenous patches of informal settlements around the city.

Based on analysis of existing land use data of the study area, it is hypothesized that a development pattern exists, whereby informal settlements at a particular location will grow up to a certain size limited by the constraints of the site and then leapfrog to a new location, where growth will again take place.

In order to test the validity of the leapfrog development hypothesis, a hybrid automata based model is proposed. In the proposed model, the factories and the workers are modelled as mobile automata, while the land units are modelled as fixed automata. The CA and the ABM are tightly coupled in a cyclical loop. The local suitability of parcels of land is modelled using CA while the location choice behaviour of the factory and worker agents is modelled using ABM. In each iteration of the loop, the CA is used to assign suitability scores for different activities to each land parcel and the agents in the ABM then make location choices based on these suitability scores. The conceptual framework is shown in Figure 2.

In order to reduce the complexity of the modelling task, this paper will focus only on the informal settlement dynamics (see the right hand side of Figure 2),

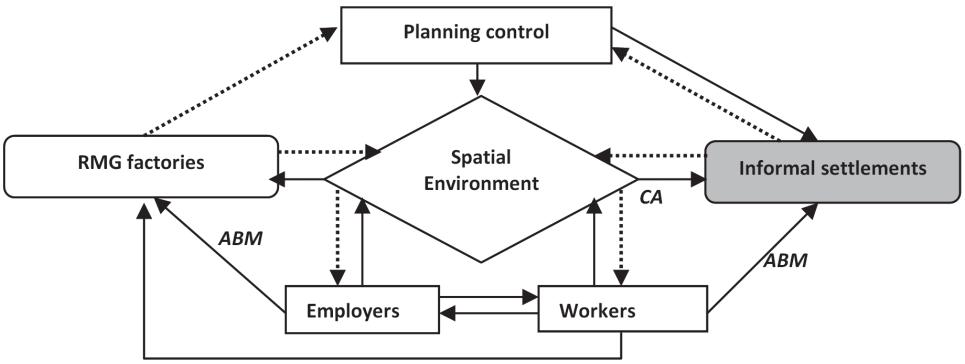

Figure 2. Conceptual framework of the hybrid automata model.2

including a CA for assigning suitability scores to parcels of land, and an ABM for modelling the worker location choices. RMG factories will therefore not be modelled as automata, but will instead be defined as static entities based on the time-series GIS data.

2.2. MODEL IMPLEMENTATION

For automata based models, time series data is required. From the detailed land-use data for the study area (e.g. construction year), the relevant data are sliced into three time series, for the years 1985, 1995, and 2005. The base year is selected as 1985 as this is considered to be the year when the RMG started to grow significantly.

The main aim is to demonstrate the validity of the leapfrog development pattern using a hybrid automata model. A hybrid model will be developed, and a set of transitional rules will be created for both the fixed and mobile automata. The temporal resolution or time step is considered one year. Starting from the 1985 dataset, the model will be run for 20 time steps in order to get a pattern of informal settlements for the years 1995 and 2005. The output generated by the model will then be compared to the actual datasets for 1995 and 2005.

The time-series data is created using ArcGIS, and the automata model is implemented in NetLogo, an integrated automata modelling environment. The shape file for the base year is first created in ArcGIS and then imported into NetLogo. The area of study is represented using a square cellular grid with a spatial resolution of two meters, where each grid cell is described as a *patch*. Each patch is assigned certain attributes that describe the patch. For example, a patch may be an RMG factory, an informal settlement, a water body, and so forth.

For informal settlements, patches are defined as being either habitable or non-habitable. For the 1985 data set, all patches in areas within the city that are vacant are assigned as being habitable. A habitable patch can be in one of three states: *empty* habitable patches have zero residents, *occupied* habitable patches have one resident, and *full* habitable patches have two residents.

The transition rules for the CA and the ABM are then defined based on these patches. The transition rules for the CA assign a suitability score to each habitable patch, and the transition rules for the ABM define how agents choose which habitable patch to settle on.

2.2.1. CA transition rules

The CA transition rules assign a suitability score to each habitable patch based on the local factors that are assumed to have influence on the workers' locational

preference. These factors include proximity to RMG factories, proximity to existing informal settlements, presence of vacant public land and so forth. These factors are selected based on the analysis of the time series GIS data, field observation, and expert opinion.

The transition rules use two methods for describing the local conditions of a particular patch: the neighbourhood method and the distance method. The neighbourhood method examines the patches that are immediately adjacent to the current patch. In this case, the von Neumann neighbourhood is used, comprising the four patches orthogonally surrounding a central patch. The distance method examines patches further away, and uses a distance rule. The scoring system uses a scale from 10 to 1, where 10 indicates that the patch is highly suitable for informal settlement. The CA transition rules are shown in Table 1.

The above rules only apply to habitable patches. However, over time, patches may change their land use due to a variety of reasons. Such changes are land use type can be handled by special transition rules, referred to as *transformation rules.* In this version of the model, one set of transformation rules have been implemented to account for the phenomena whereby workers will create informal settlements directly adjacent to or over water bodies. Patches adjacent to or over water bodies can become habitable if all other habitable patches in the vicinity are full. Under these conditions, the pressure is deemed sufficiently high to result in informal settlements encroaching onto the water bodies. In future, transformation rules for other types of phenomena will be implemented, such as the

Table 1. CA Transition rules for habitable patches.

Rule Condition: RMG factories	**Rule Condition: Informal settlement**	**Rule Condition: Waterbody**	**Rule Result: Score**
Distance < 100 meter	Within neighborhood	Within neighborhood	10
Distance < 100 meter	Within neighborhood		9
Distance < 500 meter	Within neighborhood	Within neighborhood	8
Distance < 100 meter		Within neighborhood	7
Distance < 500 meter	Within neighborhood		6
Distance < 500 meter		Within neighborhood	5
Distance > 500 meter	Within neighborhood	Within neighborhood	4
Distance > 500 meter	Within neighborhood		3
Distance > 500 meter		Within neighborhood	2
		Within neighborhood	1

transformation of habitable patches to non-habitable due to the infrastructure construction projects such as road systems.

2.2.2. ABM transition rules

An ABM has been implemented to model the location choice of worker agents. For this demonstration, a very simple model is developed. In future, it is planned to elaborate this model in more detail.

The main source of settlement growth is due to new immigrants arriving in the city. Therefore, at each time step, a fixed number of worker agents are added to the city, and randomly assigned to work in the RMG factories in existence at that point in time. Though the annual immigrants are about 100,000, in this model the number of worker agents being added to the city is set to 2000 per year. Hypothetically, each working agent is considered to be equivalent to 5 persons in reality due to the system limitations of NetLogo.

Once the worker argents are assigned to factories, they then need to choose where they are going to settle. To facilitate this choice, the vacant and occupied habitable patches within a certain radius of the factory are first sorted according to their suitability score (as assigned by the CA). Each worker agent then selects the highest scoring available patch. Once they settle on a patch, the number of residents residing on that patch will be incremented by one. (Vacant patches become occupied, and occupied patches become full).

2.3. MODEL RESULTS

The hybrid model was run for a period of 20 years in yearly time steps, using the 1985 data set as a starting point. At five yearly intervals, visual maps of the simulation results were generated that show the extents of informal settlement growth. These simulated maps allow the gradual growth of the settlement to be better understood. The maps are shown in Figure 3.

For the final simulated 2005 map, the results are visually compared to the 2005 map showing the actual observed condition. It is found that there is significant similarity between the observed map and the predicted map.

Analysing the time series data in more detail reveals that older informal settlements tend to grow larger before new informal settlements appear at other locations. The simulated model produces similar patterns of growth. However, as a result of the input parameters, important differences between simulated and actual conditions can be seen. These differences are mainly due to the parameters for the ABM, such as the number of new workers per year entering the city. Future

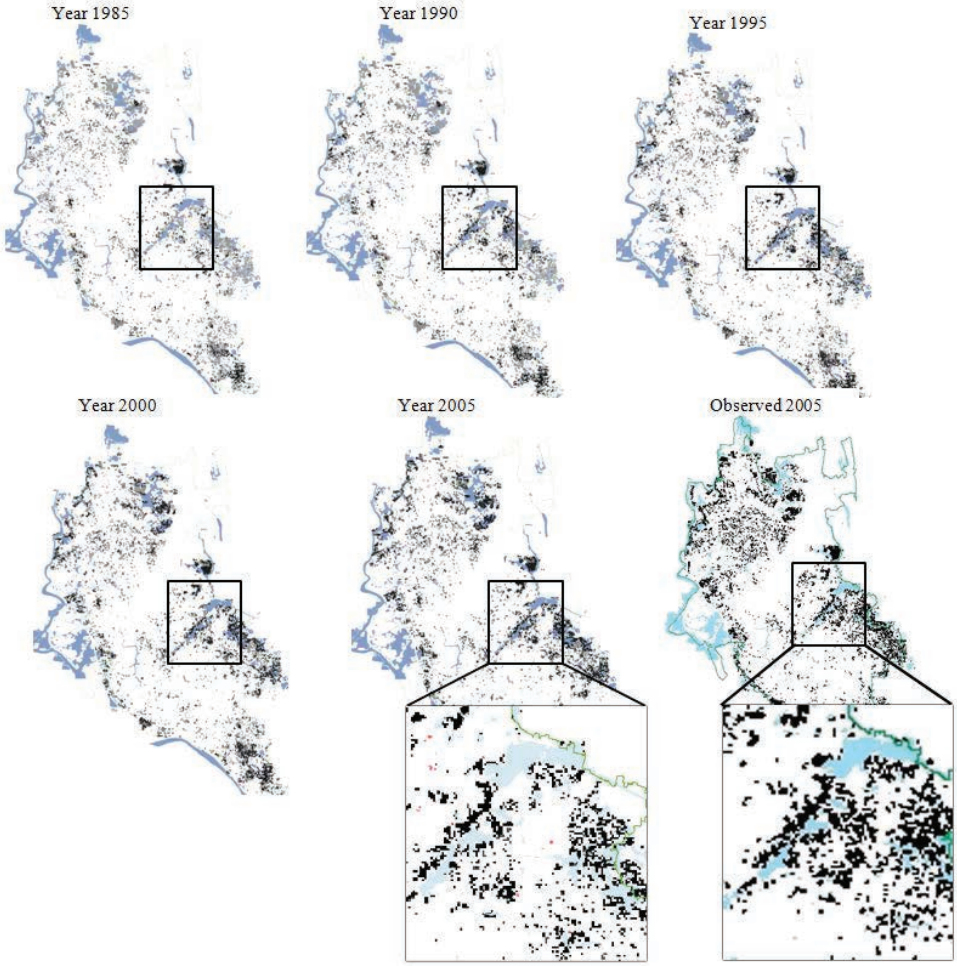

Figure 3. Comparison between the simulated and observed (last image) informal settlement patterns.

research will analyse historical and current data in order to define appropriate settings for these parameters.

3. Future Work

A hybrid model for leapfrog type urban growth has been proposed that tightly couples CA and ABM, thereby allowing both fixed and mobile automata

approaches to be used. In the hybrid mode, the area of investigation is first split into a series of small land patches. A CA is used to model suitability of patches for certain activities, and an ABM is used to model location choices for agents engaging in these activities. The CA and ABM models are executed within a cyclical loop and affect one another through the data associated with the patches. The suitability scores generated by the CA will be used by the ABM, while the location choices generated by the ABM will be used by the CA.

The proposed hybrid model has been demonstrated by applying it to a case-study in Dhaka city for simulating the growth of informal settlements associated with RMG industries. Visual comparison of the actual and predicted maps showed significant similarity. These initial results suggest that the proposed hybrid model may be of value for simulating such leapfrog type urban growth.

The proposed hybrid model is in its early stages of development. Various types of sensitivity tests and validation processes are yet to be performed. A three phased validation process is proposed for this model, borrowed from Hill and Lindner (2010).

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References

Alam, M. and Rabbani, M.: 2007, Vulnerabilities and responses to climate change for Dhaka. *Environment and Urbanization*, **19**, 81–90.

Ahmed, S. J., Bramley, G. and Dewan, A. M.: 2012, Exploratory growth analysis of a megacity through different spatial metrics: A case study on Dhaka, Bangladesh (1960-2005), *URISA*, **24**(1), 9–24.

Barros, J.: 2004, *Urban Growth in Latin American Cities: Exploring urban dynamics through agent-based simulation*, PhD Dissertation, Bartlett School of Graduate Studies of Architecture and Planning.

Batty, M.: 2007, *Cities and complexity: understanding cities with cellular automata, agent-based models, and fractals*, The MIT press.

Benenson, I. and Torrens, P. M.: 2004, *Geosimulation: Automata-based modeling of urban phenomena*, Wiley.

Benguigui, L., Czamanski, D. and Marinov, M.: 2001, City growth as a leap-frogging process: an application to the Tel-Aviv metropolis, *Urban Studies*, **38**(10), 1819–1839.

De Smith, M. J., Goodchild, M. F. and Longley, P.: 2007, *Geospatial analysis: a comprehensive guide to principles, techniques and software tools*, Troubador Publishing.

Hill, A. and Lindner, C.: 2010, *Modelling informal urban growth under rapid urbanization: A CA based land-use simulation model for the city of Dar es Salam, Tanzania*, PhD Dissertation, TU Dortmund.

Hoque, D. M. S., Debnath, A. K. and Mahmud, S. M. S.: 2007, Impact of Garment Industries on Road Safety in Metropolitan Dhaka, *Proceedings of the Eastern Asia Society for Transportation Studies*, 2007.

Islam, N.: 2006a, Bangladesh, *in* B. Roberts and T. Kanaley (eds.), *Urbanization and sustainability in Asia: Case studies of good practice*, Asian Development Bank.

Islam, N.: 2006b, *Slums of urban Bangladesh: mapping and census, 2005*, United States Agency for International Development report.

Longley, P.: 2005, *Geographic information systems and science*, John Wiley.

Masum, F.: 2009, Urban Fringe Management and Role of Good Governance: Integrating Stakeholders in Land Management Process, *7th FIG Regional Conference*, Hanoi, Vietnam.

Mottaleb, K. A. and Sonobe, T.: 2011, An Inquiry into the Rapid Growth of the Garment Industry in Bangladesh, *Economic Development and Cultural Change*, **60**(1), 67–89.

Rashid, S. F.: 2009, Strategies to reduce exclusion among populations living in urban slum settlements in Bangladesh, *Journal of health, population, and nutrition*, **27(**4), 574–586.

Sietchiping, R.: 2004, *A geographic information systems and cellular automata-based model of informal settlement growth*, PhD Dissertation, The University of Melbourne.

Torrens, P. M.: 2001, *A hybrid geocomputation model for operational land-use and transport simulation*, Annual Association of American Geographers Meeting, New York.

Torrens, P. M. and Nara, A.: 2007, Modeling gentrification dynamics: A hybrid approach, *Computers, environment and urban systems*, **31**(3), 337–361.

Vincent, O. O.: 2009, Exploring spatial growth pattern of informal settlements through agent based simulation. MSc thesis, Utretch University; Delft University of Technology; Wageningen University; International Information for Geo-Information Science and Earth Observation.

World Bank: 2007, "Bangladesh-Dhaka: Improving Living Conditions for the Urban Poor". Available from: <https://openknowledge.worldbank.org/handle/10986/7686> (accessed on 6 December 2012).

Wu, N. and Silva, E. A.: 2009, "Integration of genetic agents and cellular automata for dynamic urban growth modelling". Available from: <http://www.biodiverse.unsw.edu.au/geocomputation/proceedings/PDF/Wu_and_Silva.pdf> (accessed on 6 December 2012).

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 601–610. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

FEATURE RECOGNITION AND CLUSTERING FOR URBAN MODELLING

Exploration and analysis in GIS and CAD

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Abstract. In urban planning exploration and analysis assist the generation, measurement, interpretation and management of the modelled urban environments. This frequently involves categorisation of model elements and identification of element types. Such designation of elements can be achieved through attribution (e.g. 'tagging' or 'layering') or direct selection by model users. However, for large, complex models the number and arrangement of elements makes these approaches impractical in terms of time/effort and accuracy. This is particularly true of models which include substantial numbers of elements representing existing urban fabric, rather than only newly generated elements (which might be automatically attributed during the generation process). We present methods for identification and categorisation of model elements in models of existing and proposed urban agglomerations. We also suggest how these methods can enable exploration of models, discovery of identities and relationships not otherwise obvious, and acquisition of insights to the models' structure and contents which are not captured, and may even be obscured, by manual selection or automated pre-attribution.

Keywords. City information modelling; data mining; feature recognition; geometric-content-based-search; urban typologies.

1. Introduction

A fundamental assumption of urban design (more so than -planning) is that urban forms influence the working of urban structures. Thus, not all urban activities and

processes can be accommodated by identical (or nearly homogeneous) structures, but instead variegated forms are needed. The scale(s) at which such variety are needed and would be detectable also vary, and it is not always at an 'urban' scale that important differences occur which influence the life of the city. For example, a wide range of residential, commercial, educational, cultural and other activities can be accommodated within apparently identical block structures of Barcelona's Eixample. Yet in most cities the blocks and buildings, street patterns, open spaces and other basic urban elements do vary in form, by accident or intention. This is generally viewed as a positive characteristic for urban agglomerations to have, though at some threshold variety may come to seem excessive (Lynch, 1960). Thus, legibility of the city is achieved by some balance of predictability and surprise, of uniformity and variation, neither homogeneous nor random. The recognition of the need in the city for variation with order fits to the concept of urban typologies, not just at the level of entire agglomerations (city types) but also at the level of their elements (block types, street pattern types, etc.) The effort to read and project cities in terms of typologies also aims to support planning and control, for example in terms of predictability based on the assumption that the workings of particular types and the interactions among them are sufficiently understood (Branch, 1985). Yet no general consensus exists regarding exactly which types would adequately capture the characteristics of cities, which suggests a need for flexibility in defining and discovering types, achieved through ongoing processes of categorization.

That processes of categorization, or of 'typifying', are ongoing rather than fixed has been well demonstrated elsewhere (Bowker and Star, 1999), and we take it as given that in urbanism types are largely cultural constructs rather than 'truths' (Habraken, 2000). In either case, however, designers and planners working with large models of urban agglomerations can benefit from tools that help them make sense of the models and the modelled entities by categorizing (and re-categorizing) through analyses of the data available. Furthermore, new methods may induce the emergence of types otherwise not identifiable. Such a possibility is especially relevant in a field where ambiguity is a constant factor, as in the case of the urban environment.

In this paper we present and compare some methods for analyzing and categorizing urban forms which can help urban designers both to make sense of the structure and workings of existing urban agglomerations (towns, cities, formal or informal) and to find potential problems and opportunities in their future development. The methods on which we focus are 'clustering' (Agrawal et al., 1998; Witten and Frank, 2005) and 'user-guided feature recognition' (Chaszar, 2011a, 2011b). These methods both proceed from data contained in digital urban models - whether GIS or CAD - and process these data to find similarities and differences of possible significance. Finding such categories, patterns and other relationships among elements of the urban fabric enables designers to draw conclusions about existing conditions and also to take action when needed by proposing changes to

those conditions – especially, in the present case, physical conditions, in contrast with regulatory, policy and other possibly relevant changes.

The abilities conferred by methods such as those described here are important for various reasons. First, while models of existing urban conditions are often annotated or associated with data describing the functions (actual or legislated) and activities of particular buildings, blocks and/or parcels, such data may be unavailable, missing or incorrect. Analysis of forms can then be supplementary and may enable the finding of inconsistencies in the data. Second, projected urban designs may also include data denoting the intended uses of urban elements, but the reading of potentials by the designers themselves may under-represent the range of possible readings. Analysis of forms can then be exploratory, amplifying the models' roles as 'learning devices' (Hatchuel, 2002). The identification of possible correspondences between shapes and existing or future uses can to a certain extent be made without recourse to such techniques, of course; however, (semi)automation of the analysis as described here can be very valuable as a practical matter when models are large – consisting of hundreds, thousands or more elements – and it can also enable detection of more subtle similarities and differences than would a more conventional, 'manual' approach (Chaszar, 2011a, 2011b).

In the next section we review the context of the problem, briefly describing the practice of City Information Modelling (CIM) and related practices as well as some relevant challenges encountered within these practices. We then present a set of alternative methods for exploring and navigating the contents of such models, focusing on 'clustering' and 'user-guided feature recognition' utilising mainly geometric characteristics of model elements, though adaptable also to include topological and non-geometric data. Subsequently we describe the urban model on which tests were performed, present test results, and discuss how the application of these methods improves model users' abilities to analyse and interpret City Information Models and other models of urban environments.

2. Context – Practices and Problems

CIM here is understood as: an urban design environment integrating design and analysis tools allowing for the manipulation of designs not just through geometric parameters but also by manipulating the design attributes including some qualitative properties (Beirao et al., 2009). GIS tools are normally used in the analysis of urban environments by querying geographic databases, usually resorting to structured query languages (SQL) (Egenhofer, 1994). In the practice of City Information Modelling we stress the importance of integrating the analytical platform with the design platform maintaining the ability to perform the analysis tasks; in this case being able to analyse proposals integrated in a context and easily changing them. We also see that the GIS environment has only very basic tools to enable queries

based on geometrical characteristics of the urban environment. As discussed above, a typical analytical task would be finding particular urban types within an urban context. Typology identification can be particularly useful in contexts with incomplete or sparse databases, still a recurrent problem in many countries. Furthermore, in the context of developing countries it is often impossible to keep an updated database due to fast informal developments as well as to the difficulties in accessing the emerging areas for data survey. In these latter situations, many times the only updated easy-to-access element is an aerial photo from which only shape and a few other properties may be extracted. Typically, in such situations the designer is forced to rely on some kind of process to further fill the gaps in information.

In what follows we first describe the two methods of concern and describe their application to a particular urban model, contrasting the results obtained. We then discuss these findings in terms of their significance for future work with urban models and for future development of the methods.

3. Methods – Clustering and UGFR

The 'clustering' approach comprises a number of largely automated, statistically based methods of detecting correlations among groups of items via their attributes. The attributes examined can be data of any kind (e.g. economic, demographic, etc.), including geometric data like length, perimeter, area, etc. 'Clusters' are formed on the basis of the degrees to which the analysed items' attributes are identical or similar. While clustering analyses can be performed using all available attributes of the analysed items, more commonly some subset of attributes is chosen for analysis, which gives a degree of user-control, if not actual interaction. Subsets of attributes are defined considering meaningful correlations which may be conclusive for the identification of types or for classification in general (Gil et al., 2012). Clustering methods require also in certain cases that users outwit redundancy in the data to avoid classifying as a type what may be several expressions of the same attribute and not a real cluster of different attributes. Such statistical methods may be used to identify and classify different block and street types. It should be stressed that the attributes used in this example are all numerical and extracted from the geometry in a GIS environment (from a shapefile). Some of the attributes are directly obtained from the geometry and others calculated from basic meaningful relations among the primary ones (e.g.: FAR – floor area ratio, GSI – ground space index, OSR – open space ratio). All these attributes are then stored in a database where the statistical analyses and clustering are subsequently performed.

The 'user-guided feature recognition' (UGFR) method detects similarities and differences among analysed items by comparing each item to a 'feature vector' which describes the attributes of interest. Note that whereas 'attributes' tend to be single data items attached to a model element (or sub-element), 'features' tend to be emergent

characteristics of the attributes, elements and/or sub-elements. While this is a common approach in most object recognition methods, most such methods aim to define a comprehensive feature vector – or even a 'vector of vectors' – which can capture all features (or attributes) of interest needed to identify a particular object type and distinguish it from other types (Tangelder and Veltkamp, 2008). This normally aims for and leads to a fully automated analysis process with no user control. In contrast, the 'user-guided feature recognition' method applied here aims to focus on salient features as chosen by the user, and allows for user-control via selection and/or editing of the features considered salient for discriminating types or otherwise significant in terms of their urban nature. While 'user-guided feature recognition' was developed specifically to deal with geometric data, it could also be extended to include any other sorts of attributed data, like 'clustering': use, physical conditions (ground type, water and other resources), number of entrances, demographics, etc. In any case, the method gives a visual, easy to assess, view of specific geometry-based properties of the components of the urban environment (Chaszar, 2011a, 2011b).

These geometric-content-based search and classification methods are complementary to others such as data queries and clustering by data mining the geographic database (Gil et al., 2012), based on traditional GIS platforms and geographic databases. The complementarity of these methods can be further highlighted by pointing out that the results obtained from UGFR can also be subject to clustering for finding other kinds of correlations among properties of an urban environment which may be used to fine-tune a typology search procedure. The main difference in the proposed method is that complementary results may be achieved by searching particular geometric features. Whereas conventional data queries typically only retrieve model elements explicitly attributed with the specified properties, the user-guided methods enable selection via derived properties as well. And while data mining identifies clusters of elements with cohering sets of properties, it tends to ignore properties found in multiple clusters, which may nevertheless be important in characterising the types generated.

The methods proposed are also of interest when the geographic information is limited but the geometric information is relatively complete, and in particular in the preparation of the working base in an area lacking good reliable geographic information. In many countries, geographic information is many times not much more than flattened geometric information not correctly classified nor attributed (e.g. layered). It may be particularly useful in the case of emergent settlements where the information is usually insufficient and constantly growing and mutating. In such circumstances the first steps of the procedures aim at classifying all geometric representations in order to correct, update and complete the database. These procedures typically resort to visual recognition of geometrical features in the representations. The proposed methods support this activity through semi-automated, user-guided feature recognition. Moreover, because UGFR runs directly on the geometric model

(within the CAD environment) the method becomes quite interactive with the design process easily allowing analysis at different stages of design development. The results of our testing, presented below, indicate that such methods can contribute to the interactive flow of information during the design decision process, whether this process involves comparing different scenarios of urban design/planning or refining designs/plans to meet particular goals, such as the development of adaptable urban systems capable of accommodating rapid transformations of contemporary societies.

4. Models and Results

We performed tests for the research described here using models based on data from an existing urban unit, a cluster of small villages linked by a collection of industrial and commercial facilities focused on stone quarrying and processing. The present urban structure results from different occupations and transformations through time with different morphological characteristics related with the dominant activity of each period. The urban fabric thus comprises rural structures later occupied by industrial facilities (storehouses and factories), structures dependent on existing quarries, and new suburban housing developments. (The settlements are 30km from Lisbon).

The models include data pertaining to physical structures and features (e.g. buildings, streets, waterways) as well as geometrically describable non-physical features (e.g. property lines, administrative zones) and also other non-physical data attributed to the geometric items (e.g. population, income, land use). These data were originally contained only in a GIS model, but the geometrically describable items were exported to a CAD environment for more advanced visualization and to enable use of the UGFR tools. The model comprised approximately 3000 geometric elements, of which approximately 2000 were buildings, a modest size for urban agglomerations but already too large for effective analysis by 'manual' means – i.e. mainly visual inspection, with subsequent selection and colouring, assignment to CAD file 'layers' and/or other means of annotation.

Application of the 'clustering' method results in categorizations that capture more detailed and in-depth information than current manual procedures. Gil et al. (2012) clearly showed the capacity of the statistical methods to capture, for instance, several types of peripheral blocks that would probably be classified as a single category if traditional morphological analysis had been used. Additionally, clustering allows identifying the variability range of the parameters in each type and to pinpoint the characteristics of the local archetype – i.e. centroid – for each cluster (type). However, as an 'unsupervised learning' technique, it allows only minimal scope for user interaction.

Applying the UGFR method resulted in various user-selected categorizations of buildings according to various criteria, including simpler size-based and more complex shape-based ones. For more detailed discussion of the UGFR interface and

evaluation logic, readers are referred to Chaszar (2011a, 2011b). Size-based metrics include area, volume and volume-area ratio, as well as maximum and/or minimum dimensions. Shape-based criteria also may depend in the case of UGFR on some dimensional information (in contrast with many other object/feature recognition methods which are scale-free), but they can also involve more complex calculations using the basic geometric data. Some simple example categorizations by shape are 'tower-like' and 'slab-like' buildings. Note that reporting of search/classification analysis results can be either binary – i.e. a model item/object either meets or does not meet the stipulated criteria – or else give a more nuanced feedback, in which degrees of criterion satisfaction are also indicated (similarly to relevance ranking in common search engines). Although not implemented here, more complex feature recognition queries can also be composed, evaluating objects for general characteristics such as their 'roughness', 'porosity', etc., as well as for more specifically urbanistically motivated shape properties which can further influence the objects' roles within the urban ensemble.

5. Discussion

On the basis of the investigations described, we can make some observations at varying degrees of generality regarding the use of 'clustering' and UGFR analysis methods as well as regarding the use of GIS and CAD for such analyses. Specifically within the research reported here, it was evident that even relatively simple size-based metrics can be effective in giving a quick overview of building/block type distributions. The more complex shape-based categorizations, however, can capture other characteristics which may be relevant to the existing or future potential roles of urban elements. UGFR clearly identifies some of the recurrent building types in the study area. For instance, industrial buildings pointedly stand out in a search for predominantly flat buildings ('slab-like buildings'). When combined with large area building search the type is captured in almost every instance. House types imply more refined analyses. Contemporary single houses tend to be a bit larger (and also more 'square like') than the older traditional houses. The latter tend to have simpler polygons as footprint albeit being predominantly irregular while the former, although more regular, tend to have more complex polygons as footprint. Size matters, of course, certainly in terms of the character of an urban area as well as in other more technically defined performance criteria. Designers generally get a quick and perhaps unconscious sense of variations of granularity in the urban fabric without recourse to analysis tools or even to software (as from a simple map), but adding abilities to process the relevant data reliably, to define regions based on categories of element sizes, to visually record and easily communicate such results, can all assist the tacit and explicit reasoning processes involved in design and planning. Shape-based analyses, on the other hand, underscore the fact that categories are malleable, and that any

particular item may be grouped differently, depending on the criteria chosen. While a 'clustering' approach tends to assume that 'more data is better' for forming durable categories based on correlations among all available attributes (all presumably weighted equally), a UGFR approach emphasizes the importance of judgement, exercised through selection of relevant attributes and of their relative importance.

More generally, although the two methods as explained here are not that different in terms of the parameters directly extracted from the model (length, width, orientation, area, perimeter and so forth), they differ greatly in terms of their working environment: UGFR allows for more interactivity with the design process as it works within the CAD environment. All of the analyses performed could in principle be programmed and executed within a GIS environment, provided that this includes sufficiently rich geometric data as well as functions capable of manipulating those data in geometrically sophisticated ways. In practice, such capabilities are much more characteristic of CAD environments, and practically absent from GIS ones, so the continued need for transferring data seems likely. Another option may be to implement the clustering and/or UGFR algorithms within a more sophisticated database environment such as PostgresSQL, which would allow formulation of more complex queries and allow also the execution of functions to derive object (or even inter-object) properties from the given attribute data – as does UGFR within CAD – and/or otherwise process the data – as for clustering or other statistical and data-mining procedures. However this again would separate the analysis functionality from the design environment, tending to hinder the formulation and testing of insights by the model users.

As such systems accommodate varying degrees of user-interaction, the more interactive versions are more conducive to model/data exploration and thus more supportive of the role of models as 'learning devices' (Hatchuel, 2002). This in turn we would expect to lead to more and better insights gained, and thus to better comprehension of existing conditions as well as better design and planning (which, if competently carried on, may even result in better cities). Still, the level of interactivity offered poses challenges of usability and comprehensibility. More specifically, a system with very many settings and controls for customization of analyses by users may become too cumbersome for general use, instead appealing only to relatively few enthusiasts willing to devote considerable effort to mastering them. On the other hand, inadequate controllability (via user interaction) can result in misleading analyses due to inappropriate assumptions built into the system – e.g. regarding salience of data, processing of data, the number of types/categories, etc. – and/or due to inappropriately detailed (or approximate) analyses being the default, perhaps only, option.

All in all, it is apparent that both 'clustering' and 'user-guided feature recognition' methods are potentially helpful in analysis of urban models, especially but not exclusively those including geometric data. The exact ways in which such

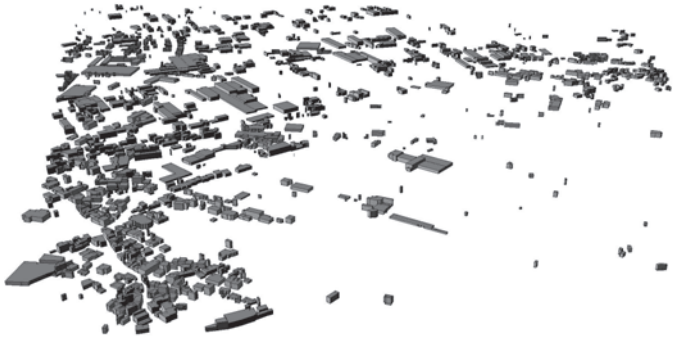

Figure 1.

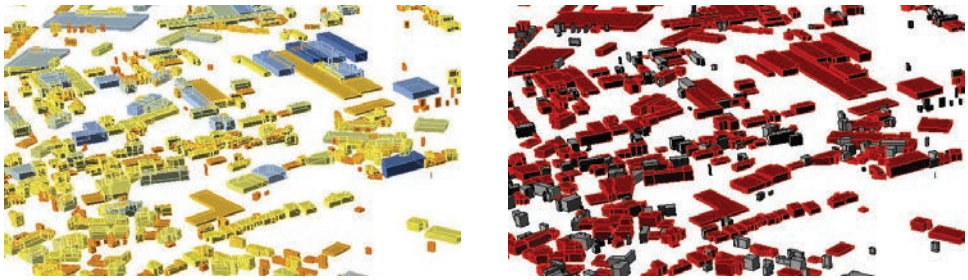

Figure 2 (a) & (b).

methods are applied, and the ends in which they result depend of course on the aims and abilities of the designers/planners using them, as on the overall processes of conceptualization and execution in which they are embedded. The combination of both methods may in future work enable the possibility of capturing even more refined patterns or types, identifying their attributes, the variability range of their parameters and even their archetypes.

6. Conclusion

We have presented methods for analyzing the forms of urban structures – in this case particularly blocks and buildings – which can help designers to comprehend the current conditions of cities and to project their futures. Different approaches to finding possibly significant similarities and differences in urban forms have been described, utilizing mainly geometric data contained in GIS and CAD models of urban agglomerations. These approaches have varying types and degrees of user-interactivity, which may make one or the other more or less suitable for particular urban analysis and design tasks. Such systems enable users to define and/or discover types of urban

elements rather than confining them to searching for pre-defined, 'known' types. This includes the ability to define/discover categorizations at varying degrees of discrimination, from very rough (e.g. all buildings over, and all under or equal to X sq.m. in footprint) to very nuanced (e.g. buildings with various degrees of self-shading on one or more relevant facades). Simple size-based metrics tend to have less discriminatory capability of course – not distinguishing between tall, long, or more compact forms of urban structures, for instance – but even within such a criterion as many categorizations may be made as desired. By working within the CAD environment UGFR becomes an interactive design support analysis tool, with advantages including: (1) providing a more intuitive reflection on the meaning of shapes and (2) bringing analysis processes closer to common design practices. Both clustering and User-Guided Feature Recognition can include also non-geometric data which may give further insights to the existing and potential future workings of the modelled cities. Further work is needed to extend such analysis methods to include other physical urban elements such as open (land and water) spaces, transportation networks, etc. Future development might also include analyses of spatial relationships among urban objects, rather than only of the characteristics of objects themselves, providing more accurate insight on, for example, the rather obscure area of public space morphology.

References

Agrawal, R.; Gehrke, J.; Gunopulos, D.; Raghavan, P.: 1998, Automatic subspace clustering of high dimensional data for data mining applications, *Proc. ACM SIGMOD*, 94–105.

Beirão, J., Duarte, J., Stouffs, R.: 2009, An urban grammar for Praia, *Proc. eCAADe*, 575–584.

Bowker, G.C. and Star, S.L.: 1999, *Sorting things out: Classification and its consequences*, MIT Press, Cambridge, MA.

Branch, M.: 1985, *Comprehensive city planning: introduction & explanation*, Planners Press, Chicago.

Chaszar, A.: 2011a, Navigating complex models in Collaborative work for integrated (and sustainable) design, *Proceedings CAADFutures*, Liege.

Chaszar, A.: 2011b, Spatial query and object recognition to support 3D digital building model use, *Proceedings EG-ICE*, Twente.

Egenhofer, M.J.: 1994, Spatial SQL: a query and presentation language, *IEEE Transactions on knowledge and data engineering*, **6**(1), 86–95.

Gil, J., Beirão, J.N., Montenegro, N., and Duarte, J.P.: 2012, On the discovery of urban typologies: Data mining the multi-dimensional morphology of urban areas, in *Urban Morphology*, **16**(1), 27–40.

Habraken, N.J.: 2000, *The Structure of the Ordinary*, MIT Press, Cambridge, MA.

Hatchuel, A.: 2002, Towards design theory and expandable rationality, *Journal of Management and Governance*, **5**(3-4), 260–273.

Lynch, K.: 1960, *The image of the city*, MIT Press, Cambridge, MA.

Tangelder, J. and Veltkamp, R: 2008, A survey of content based 3D shape retrieval methods, *Multimedia Tools and Applications*, **39**(3), 441–471.

Witten, I. H, and E. Frank.: 2005, *Data Mining: Practical Machine Learning Tools and Techniques*, Morgan Kaufmann.

DIGITAL FABRICATION AND CONSTRUCTION

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COMPLEX CONCRETE CONSTRUCTIONS

Merging existing casting techniques with digital fabrication

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Abstract. In the course of the 20th century, architectural construction has gone through intense innovation in its material, engineering and design, radically transforming the way buildings were and are conceived. Technological and industrial advances enabled and challenged architects, engineers and constructors to build increasingly complex architectural structures from concrete. Computer-aided design and manufacturing (CAD/CAM) techniques have, more recently, rejuvenated and increased the possibilities of realising ever more complex geometries. Reinforced concrete is often chosen for such structures since almost any shape can be achieve when poured into a formwork. However, designs generated with digital tools tend to have limited relation to the efficient modes of production typically used in contemporary concrete construction. A large gap has emerged between the technology in architectural design and the building industry, so that few efficient solutions exist for the production of geometrically complex structures in concrete. This paper focuses on the capabilities and efficiency of existing casting techniques both with static and dynamic formwork which, when combined with digital fabrication, allow innovative fabrication approaches to be taken. Particular focus is placed on slipforming, an approved and efficient construction technique, which until now is unexplored in conjunction with digital fabrication.

Keywords. Complex concrete structures; casting techniques; formwork; slipforming; digital fabrication; smart dynamic casting.

1. Introduction

The technological development of reinforced concrete[1] has been one great enabler of modern architecture. It is still one of the preferred materials for realising all kinds of structures, simple and complex[2], for which purpose 3.4 billion tonnes of cement were

produced in 2011 alone to make concrete (Olivier et al., 2012). Yet concrete itself is only half the picture, since it is formwork that determines what is possible to build, and which represents 35–60% of the overall costs of concrete structures (Johnston, 2008) and a significant source of waste, given that all formwork is discarded sooner or later, contributing to a generally increasing production of waste worldwide[3].

Addressing the need for innovation in the casting of concrete is an important measure. In this regard, well-established casting techniques such as (static and dynamic) slab casting and slipforming could promise efficient and waste-free approaches for the construction of complex concrete structures.

This paper considers these two casting techniques set in a general historical context, to show how these techniques developed over the 20th century and influenced the way architecture was conceived. Particular focus is given to recent research that has pioneered the combination of slipforming and robotic fabrication. For this project an innovative fabrication method was developed, in which concrete is formed using a robotic slipforming technique during the period when it changes from soft to hard material. Developed further, this technology could be used in the construction of complex concrete structures, and lead to a shift in the way structures are built.

2. Static Formwork Systems in Conjunction with Digital Fabrication

2.1. OVERVIEW OF STATIC FORMWORK SYSTEMS

The most common casting technique for concrete is slab formwork, a static casting process in which concrete is poured into a formwork that is removed after the concrete has cured. At the outset of the 20th century such formwork was traditionally made of timber shuttering supported externally by wooden frames, and was normally discarded after a single use. Due to material shortages and high labour costs, by 1910 some of the first standardized metal formworks were commercially produced for road construction (Hurd, 2005). In the 1920s architects and engineers took advantage of these modular formwork systems for concrete construction, exemplified in the works of Walter Gropius, Le Corbusier and Ernst May, who helped lay the basis for what is today know as prefabrication. In the 1950s prefabrication techniques were adapted at a larger scale in the housing sector (Schmidt and Hassler, 2004), as well as for the construction of more complex structures, such as those seen in the works of Pier Luigi Nervi (Nervi, 1965) and Felix Candela (Moreyra Garlock, 2008). Their innovative designs were based on the search for appropriate geometrical formulations for structures corresponding with inherent material properties and constructability. An early example is the spherical vault of the Sports Palace in Rome; a structure composed of 19 different kinds of prefabricated elements (Tullia and Poretti, 2005). Despite such innova-

tive approaches in terms of structure and fabrication, most advances in prefabrication since the 1950s have been mainly directed towards more efficient and faster serial mass production of similar and standardized building components.

2.2. DIGITAL TECHNOLOGY IN CONJUNCTION WITH STATIC FORMWORK SYSTEMS

Rapid developments in CAD/CAM technology have in the last decades augmented the design possibilities for complex concrete structures generally requiring custom formworks. A pioneering example is the Nationale-Nederlanden Building in Prague, Czech Republic (Glymph, 2009) or more recently the Spencer Dock Bridge in Dublin, Ireland[4]. The formworks applied to erect structures as these are generally fabricated using a CNC-mill to carve material out of a homogenous piece of foam or wood. These formworks are usually discarded after a single use. Until now, this wasteful production process has been the most efficient technique available for making custom formworks for complex concrete constructions.

However, a number of companies and research projects have also developed innovative formworks that combine digital technology with traditional formwork systems, such as those developed by PERI, a German producer of traditional scaffolding systems, ADAPA, a Danish company for adaptive concrete construction, and by the Chair of Architecture and Digital Fabrication at ETH Zurich, in their TailorCrete research project.

PERI (2012), for instance, has advanced with a system of concrete moulds which can be used for both flexible single-curved formworks and custom double-curved formworks. The company has also developed software which can automatically determine the optimal formwork for a given complex concrete structure. This innovation in both software and formwork technology is mainly applicable for larger curvatures, which generally do not cover the geometrical resolutions which can be achieved with milling.

In contrast, the company ADAPA (2012) has developed a higher-resolution flexible formwork system for prefabrication, employing a “non-porous flexible membrane”, which is adjusted into place via computer control (Raun and Kirkegaard, 2012). The membrane itself is used as formwork for the production of double-curved concrete panels, which can be reconfigured and reused (ADAPA, 2012).

A similar approach is taken by TailorCrete (Gramazio and Kohler, 2011), for which a digitally controlled flexible mould system was developed. It uniquely uses a flexible mould system off-site to fabricate recyclable wax formwork inlays, which are subsequently brought on site and inserted into a standardized formwork system. This innovative system for the construction of complex concrete structures combines the advantages of standardized modular formwork technology

with an effectively waste-free reusable-wax system for the construction of double-curved structural concrete elements (Oesterle et al., 2012).

Despite the limitations in the achievable curvature and resolution of each of the described projects, they all successfully demonstrate new approaches for the fabrication of complex concrete structures, which combine century-old fabrication techniques with contemporary digital technologies. The projects described here demonstrate the potential for a sustainable and effective waste-free casting system for the fabrication of complex concrete structures.

3. Dynamic Formwork Systems in Conjunction with Digital Fabrication

Slipforming, a dynamic casting process, was invented in 1899 by the engineer Charles F. Haglin in collaboration with the grain company owner Frank Peavey. Slipforming is a single-step process, in which concrete is continuously poured into a delaminated formwork that moves vertically in a speed set according to the rate of the hydration of the concrete, so that the material is self-supporting when released by the formwork.

One of the first known structures erected with this technique (Figure 1) was a 20-meter-high reinforced-concrete grain elevator, for which the slipforming was driven by hand (HCRS, 1978).

In 1944, the invention of centrally controlled hydraulic jacks (Bygging-Uddemann, 2011) transformed slipforming into an almost automated casting system, which enabled tall structures to be erected efficiently. Today slipforming is mostly applied for the construction of tower cores, bridge piers, power plant cooling towers, chimney shafts, pylons, the legs of oil-rig-platforms and structural

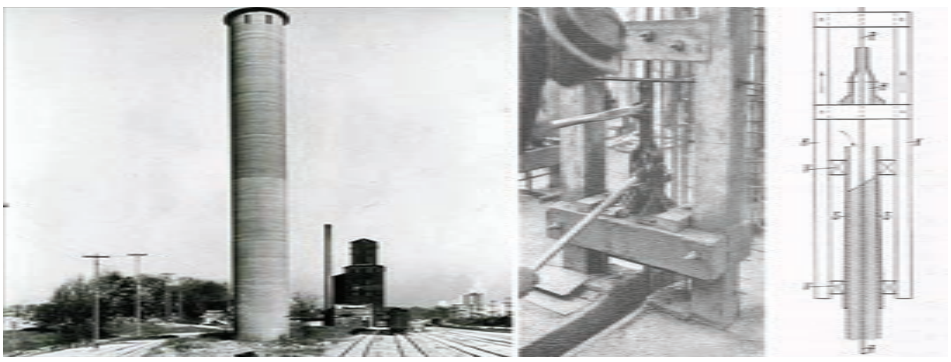

Figure 1. Left, Peavey-Haglin experimental concrete grain elevator, St. Louis Park, 1908 (Heffelfinger, 1960), Right: Manually driven slipform (Jegher, 1930).

facades of high-rise buildings (Nawy, 2008); notably used to produce some of the tallest free standing structures in the world.

Until now, slipforming remained a technique extensively used in practice, as it enables a faster rate of construction, with the use of little formwork. However, it is constrained with respect to the freedom necessary for producing complex concrete geometries. Furthermore, this technique is generally limited to structures over 10m tall, because of a high initial workload and set-up costs.

Re-evaluating this existing and efficient construction technique in conjunction with digital fabrication could not only make this system economically viable for structures below 10m, but would also include the inherent freedom of forming, without the need for an individually made formwork for each structure produced. Such approach promises an almost waste-free construction technique for complex concrete structures.

3.1. SLIPFORMING AND DIGITAL FABRICATION

A recent research project at ETH Zurich, the subject of this paper, has pioneered the first known combination of slipforming with digital fabrication techniques.

For the project, a dynamic casting technique was developed in which typical hydraulic jacks are replaced by a 6-axis robot, resulting in what we term “robotic slipforming”. In robotic slipforming, concrete is formed by a robot in the period when the concrete changes from soft to hard material, allowing the structure to be dynamically shaped by the trajectory of the formwork.

Robotic slipforming promises significant potential in terms of formability and scale, and to eliminate the need for serial production of custom-formworks in the construction of complex load bearing elements and structures for architectural construction.

To succeed even at a prototype-scale it was necessary to first gain understanding of the properties and behaviour of the chosen material (concrete) in the delicate period of time where it changed from soft to hard material. For this, a study was undertaken jointly by the Chair of Physical Chemistry of Building Materials (Prof. Flatt, ETH) and the Chair of Architecture and Digital Fabrication (Prof. Gramazio and Prof. Kohler, ETH). This initial study, which demonstrated a high potential for an effectively waste-free fabrication process for complex concrete structures, is described throughout this chapter.

3.2. FIRST EXPERIMENT RESULTS

The initial experiments aimed at producing a series of double-curved column sections using fibre-reinforced self-compacting mortar (SCM). The tests described

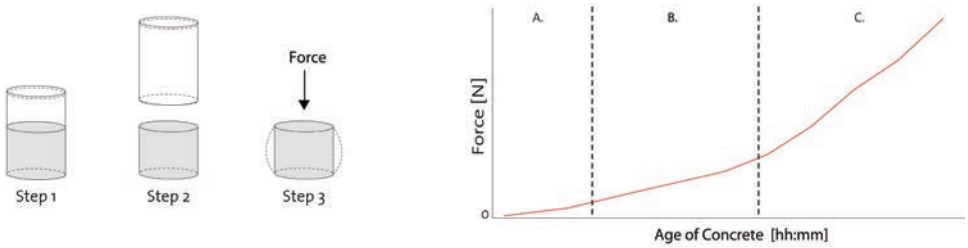

Figure 2. Left: Experiment steps: Step 1, the concrete rests in the formwork (hydration time depends on mixture); step 2, the formwork is removed; step 3, force is applied. Right: The graph of a single test session: In period A the section was not yet self-sustaining; in period B, the material was self-supporting, formable, and easy to remove from the mould; in period C the material started to crack and was no longer formable, generating high friction when removing the mould.

are all carried out using a rigid cylindrical mould coated inside with a lubricant foil. Prior to the robotic slipforming it was necessary to perform a series of load tests on small sections of fibre-reinforced SCM. These tests were used to determine its load-bearing capacity at a given time and when a column section was self-supporting. The test intervals were done over a period of two hours which allowed finding an approximate start point for the robotic slipforming (Figure 2).

The uniaxial tests alone did not provide sufficient data on either the formability of the concrete over time or the optimal slip velocity. For this, experiments were performed in the robotic slipform, where the slip-velocity was defined by maintaining a constant trajectory and age of concrete, but varying the rate of slipping, in an iterative process. The experiments shown in Figure 3 allowed us to conclude that:

- Speed A: too high slip-velocity in the initial phase causes the material to creep.
- Speed B: Too low slip-velocity; hydration occurs in the mould and generates too high friction, and therefore breakages.
- Speed C: Is the optimal velocity; slow in the beginning, to allow the material to obtain strength; with an exponential velocity, adjusted to setting of the mixture used.

Having determined an optimal slip velocity which allowed to slipform columns with a height of 65 cm in 19 min, a catalogue of double curved column designs were defined in a CAD program. The column geometry and slip velocity was then translated into the machine language of the 6-axis robot (Figure 4). The experiments revealed physical constraints in the material's limits of curvature and formability. These were fed back into the design process; the digital curvatures were adjusted to remain within the material limits.

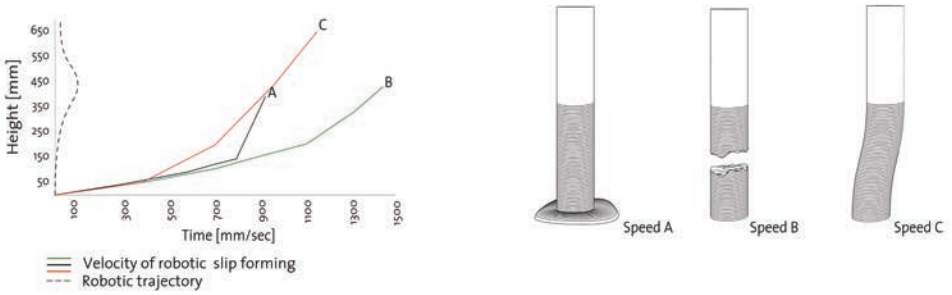

Figure 3. From left to right: Graph shows the speed curves A, B, C in relation to the height of the three experiments.

Figure 4. From left to right: Robotic set up; 65cm dynamic slipformed prototype.

These initial experiments focused on the narrow time frame in which a fibre SCM is both formable and self-supporting. Despite their focus and limitations on forming they have proven the high potential of robotic slipforming for producing complex concrete structures. However, the slip velocity and the formability of the material remains one of the major challenges in our on-going research.

3.3. FUTURE LINES OF ENQUIRY

The cylindrical formwork used in the first experiments is currently limited to curved geometries. However, studies are currently being made where a variation of rigid and flexible formworks are employed, opening up a design space which in the future might be able to vary the geometry from wall to column structures.

In the initial experiments the slip velocity was empirically defined according to the behaviour of the concrete. In the following steps of the research, a feedback

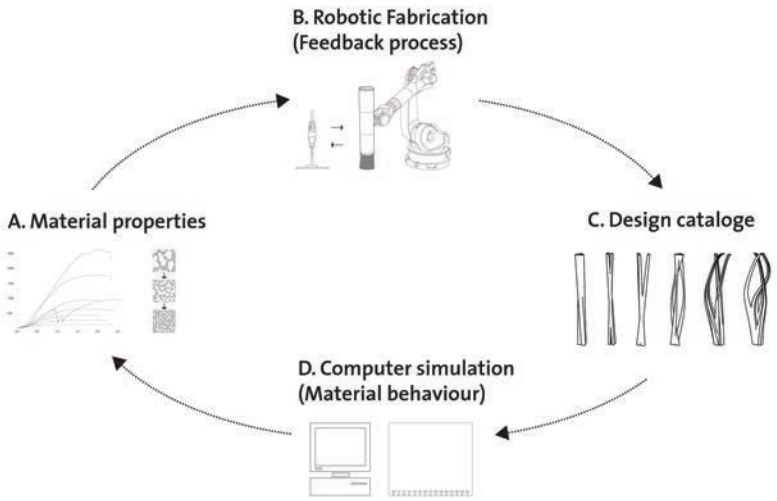

Figure 5. The research model for the development of robotic slipforming. The experiment is investigating which geometries are possible, building up a architectural design catalogue for complex concrete structure.

system is being established which enables continuous communication between the robotic slipforming and the material properties. This set up will automatically control the slip velocity and forming process in accordance to the material properties.

The feedback model takes the form shown in Figure 5, incorporating the dynamic properties of materials with design and digital fabrication. This process allows for the analysis of materials in an iterative fabrication loop and feeds the resulting material effects directly back into a 1:1 scale of production (Gramazio and Kohler, 2008).

4. Conclusion

Robotic slipforming offers a glimpse at an entirely new family of construction processes, which would be unthinkable without the integration of digital technologies.

In this kind of production technique, the properties of materials become an integrated part of the design process, unlike in conventional static formwork techniques for complex architectural concrete structures, in which material properties are largely absent in the early phases of design. It promises a shift in paradigm from a static to a dynamic adaptive manufacturing process, with which complex concrete structures can be fabricated at full scale without the need for static cus-

tom-made formwork. The role of designers in this process will be firstly to understand materials, and then develop rules to produce appropriate and desirable geometries.

Robotic slipforming promises to become a sustainable and waste-free construction technique, combining digital design with an existing and well-established construction method, potentially able to change how architectural structures are conceived in future. This research has thus begun to narrow the present technological divide between digital architectural design and currently available casting techniques for complex concrete structures.

Endnotes

1. In 1867 the invention of reinforced concrete changed this material to a fireproof material, which could take both tensile and compressive loads. This invention has radically changed the way buildings have been conceived throughout the 20th century. Further information on the topic can be found in: (Schmidt and Hassler, 2004) or (Langenberg, 2012).
2. "Complex geometries" refer here to a large number of distinct parts where little or no repetition occurs. Complex is not constrained to formal qualities but also have the intention of projects to be structurally optimised and unique in direct contrast to industrial 'standard' projects. Complex was discussed in a similar fashion at the exhibition at Centre Pompidou, Paris by F. Migayrou in 2003, though referred to as non-standard (Migayrou, 2003).
3. According to a study from 2011 80 % of the total waste production is created in the construction industry, of which 1.97 % comes from formwork timber (Llatas, 2011)
4. Spencer Dock Bridge, Future Systems, completed by Amanda Levete Architects, 2009 (NEDCAM, 2011).

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References

ADAPA: 2012, "ADAPA Adaptive Moulds". Available from: <http://adapa.dk/> (accessed 20 November 2012).

Bygging-Uddemann: 2011, "Background history". Available from: <http://bygging-uddemann.se/about-us/background-history.html> (accessed August 2011).

Glymph, J.: 2009, Evolution of the digital design process, *in* B. Kolarevic (ed.), *Architecture in the digital age – Design and Manufacturing*, Spon Press, New York, 108.

Gramazio, F. and Kohler, M.: 2011, “TailorCrete, 2009-2013”. Available from: <http://dfab.arch.ethz.ch/web/d/forschung/164.html> (accessed 31 August 2012).

Gramazio, F. and Kohler, M.: 2008, *Digital Materiality in Architecture*, Lars Müller, Baden.

Hassler, U.: 2010, *Was der Architect vom Stahlbeton wissen sollte*, gta Verlag, Zurich.

HCRS: 1978, “Peavey-Haglin Experimental Concrete Grain Elevator”. Available from: National Park Service, United States Department of the Interior <http://pdfhost.focus.nps.gov/docs/NHLS/Text/78001547.pdf> (Accessed 12 November 2012).

Heffelfinger, J. R.: 1960, “Experiment in Concrete: A Pioneer Venture in Grain Storage”. Available from: <http://collections.mnhs.org/MNHistoryMagazine/articles/37/v37i01p014-018.pdf> (accessed 30 December 2012).

Hurd, M.: 2005, *Formwork for Concrete*, 7th ed., American Concrete Institute.

Jegher, C.: 1930, Die Gleitschalung im Silobau, *Schweizerische Bauzzeitung*, **95/96**(7), 86–93.

Johnston, W. D.: 2008, Design and Construction of Concrete Formwork, *in* E. G. Nawy (ed.), *Concrete Construction Engineering Handbook*, CRC, Boca Raton, FL, 7-1–7-49.

Langenberg, S.: 2012, Das Konzept »Ersatz«? Probleme bei der Reparatur industriell gefertigter Bauteile, *Technikgeschichte*, **79**(3), 256–258.

Llatas, C.: 2011, A model for quantifying construction waste in projects according to the European waste list, *Waste Management*, **6**(31), 1083–1426.

Migayrou, F.: 2003, *Architecture Non Standard*, Centre Pompidou, Paris.

Moreyra Garlock, M. E. and Billington, D. P.: 2008, *Felix Candela: Engineer, Builder, Structural Artist*, Yale University, New Haven, CT.

Nawy, E. G.: 2008, *Concrete Construction Engineering Handbook*, 2nd ed., CRC, Baton Rota, FL.

NEDCAM: 2011, “NEDCAM Shaping technology”. Available from: <http://www.nedcam.com> (accessed 28 August 2012).

Nervi, P. L.: 1965, *Aesthetics and Technology in Building*, Harvard University, Cambridge, MA.

Kohler, M., Gramazio, F., Oesterle, S., Mirjan A. and Vansteenkiste A., 2012, “High-efficiency concrete formwork technology”. Available from: < http://www.holcimfoundation.org/T1507/Innovation_1st_prize_-_Switzerland.htm> (accessed 17 March 2013).

Olivier, J. G. J, Janssens-Maenhout G. and Peters, J. A. H. W.: 2012, *Trends in global co2 emissions*, PBL Netherlands Environmental Assessment Agency, The Hague/Bilthoven.

PERI: 2012, “Erfolgreich bauen mit PERI.” Available from: <http://www.peri.com/ww/de/index.cfm> (accessed 19 March 2013).

Raun, C. and Kirkegaard, P. H.: 2012, Reconfigurable double-curved mould, *icff 2012: second international conference on flexible formwork*, BRE CICM, University of Bath, Bath, UK, 292–299.

Schmidt, H. and Hassler, U.: 2004, *Häuser aus Beton*, Wasmuth, Tübinge.

Tullia I. and Poretti, S.: 2005, Pier Luigi Nervi’s Works for the 1960 Rome Olympics, *in* S. Huerta (ed.), *Actas del Cuarto Congreso Nacional de Historia de la Construcción*, I. Juan de Herrera, SEdHC, Arquitectos de Cádiz, COAAT Cádiz, Madrid.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 623–632. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

DIGITALLY DESIGNED ARCHITECTURAL FORM BUILT USING CRAFT-BASED FABRICATION

Weaving a complex surface as a bamboo reticulated shell

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Abstract. This paper outlines a methodology that enables the construction of complex surface forms resulting from computational design processes by manual means using non-industrial materials. The methodology is based on the craft process of weaving whereby a three-dimensional form can be produced using a flexible, linear material. Construction information from a three-dimensional digital model is communicated to craftspersons through a set of two-dimensional drawings outlining the sequence of construction and requiring only linear dimensions.

Keywords. Digital-physical; craft; non-industrial materials; weaving; reticulated shell.

1. Introduction

The physical manifestations of digital designs are most often realised through digital fabrication. This is in part because digital design and fabrication research has taken place in the developed world where skilled labour is expensive and automation is a financial necessity (Bechthold, 2004). Digital fabrication technologies require highly processed, homogenised, materials to maintain their high levels of accuracy and high tolerances and such materials are difficult and expensive to produce (Risatti, 2007; Kamath, 2009; Enns, 2010). Both the technology and the materials of digital fabrication are often financially out of reach for a majority in the developing world, but craft skills and non-industrial materials, on the other hand, are abundant. This paper outlines a methodology whereby craft based fabrication may be used to construct digitally designed forms.

2. Craft, Design, and Computation

While design and craft both start with an idea and result in the creation of a functional object, Risatti (2007) argues that a designer operates in abstract and creates a set of instructions by which to make something, rather than creating anything physical. The subsequent execution of the design to create a physical object may use either human workmanship or machines. The human workmanship involved in executing a design, according to Risatti, is not craft. While a design may be completely original, its execution must follow the set of instructions set down in the design, and every time the design is executed the resulting object will be the same. The kind of workmanship involved in executing a design may be described as the "workmanship of certainty" to use a term coined by David Pye (1968). Pye explains that when the "workmanship of certainty" is taken to its logical conclusion, the result is mechanised industrial production where the outcome of the production process is completely controlled and there is no room for variation. Instead, craft – "the workmanship of risk" – involves the making of objects in a dialogical process between the craftsperson, their hand and mind, and physical material. While a craftsperson needs to exercise precise, often repetitive, skill and control, every object made by this process is still unique and different from every other object made.

In illustrating the parallel histories of computation and industrialisation, Dutta (2007) terms the variation inherent in craft objects to be "felicitous error" (p. 212) that is a "variation from the programmed" (p. 212) and the craftsperson as a source of "fecund miscomputation" (p. 212) in the craft process where every move "bears the possibility of an incomputable deviation from the norm" (p. 212). The source of this variation originates in the dialogue between craftsperson and physical material, as described by Risatti (2007). Kamath (2009) shows that the reason that variation in craft is incomputable is due to the inability of any algorithm to predict either the outcomes of human action or the outcomes of the natural processes that create the raw materials of craft, to a degree of dimensional accuracy that is needed to describe the variation between similar craft objects.

3. The Advantages and Disadvantages of Craft and Design

The advantages of industrial mass production over craft are obvious – industrial production allows a large number of objects of a consistent quality to be produced cheaply, as opposed to craft which involves workmanship of risk. The process of design prescribes the form and shape as well as the material specifications of a manufactured object. Even if a design is completely unique (as is often the case in architecture), Risatti (2007) explains that a given design specifies a single object and has no room for variation built into it.

The disadvantage of uniformity and standardisation inherent in mass production has been overcome through the digital control of manufacturing processes

that enable mass customisation (Pine, 1999). The emergence of mass customisation has gone hand-in-hand with the digitisation of the design process.

Risatti (2007), Dutta (2007), Kamath (2009), and Enns (2010) point out that another disadvantage of industrial production is its dependence on input materials having uniform physical properties. Enns states the problem with reference to contemporary trends of digital design and fabrication in architecture:

> "Such practices constitute an unnecessarily inefficient production circuit that moves from nonstandard input such as a tree to standardised stock material such as plywood or dimensional lumber, and back to nonstandard forms through digital fabrication." (Enns, 2010, p. 118).

4. Digital Craft

Kamath (2009) looks at the dialogical process between a craftsperson and their material medium as an iterative cycle where each step in the cycle can be broken down into three parts – "sensing" (where the craftsperson studies the material and its inherent variations), "evaluating" (where the craftsperson thinks of ways to negotiate these material variations with the set performance criteria required of the object being produced), and "shaping" (where the craftsperson gives a form to the material that takes into account its non-uniformity and the performance criteria required of the object). Kamath shows how each of these three steps – "sensing", "evaluating", and "shaping" the material – can benefit from existing technologies such as 3D scanning, parametric design software, and digital fabrication respectively. While this transfer of technology from design processes to craft processes may be theoretically possible, it is still at a very nascent stage as may be seen in the work of Christian Feibig (2011).

Instead of looking at craft and design as two mutually exclusive processes, this paper illustrates a workflow that allows existing technologies of digital design to be used in a collaborative manner with craft processes so as to integrate the respective advantages of craft and design discussed above while overcoming the limitations of each.

5. The Digital Design and Fabrication of Complex Surfaces

This paper describes the design and construction of a complex roof surface in bamboo-crete using a permanent bamboo reticulated shell formwork. Bechthold (2004) outlines a tectonic strategy to construct the complex forms of equilibrium shells involving sub-dividing the shell into non-standard components that are CNC pre-fabricated and subsequently assembled on site to create some manner of temporary or permanent formwork. This formwork is used to give shape to a variety of materials such as ferrocement or strips of wood. According to Bechthold, the advantage of such a method compared to other, non-digital, methods of construction, is that digitally fabricated formwork

> "liberates designers from restrictions to regular geometry or repetitive use of identical shells for the sake of economy. The process is designed such that there are no disadvantages to uniquely shaped shells and shell segments. A maximum complexity is embedded in, and maximum value derived from the rib network that is directly generated from the digital model." (Bechthold, 2004, p. 96.)

While Bechthold (2004) refers to the construction of complex surfaces in the context of equilibrium shell structures, others such as Griffith and Sass (2006) extend this method of sub-dividing a surface into CNC fabricatable parts to other structural systems such as block walls.

6. The Digital Design of the Permanent Formwork

This paper describes a methodology by which a digitally designed complex roof surface is built manually through a craft based weaving process. The roof is to cover a living unit for visiting scholars at an educational research campus. The roof was envisaged as a hybrid reticulated shell structure (Paoli, 2007) where a funicular equilibrium surface is supported by a series of edge columns and beams. A detailed discussion of the structural system, however, is beyond the scope of this paper.

The plan of the residential unit determined the profile of the roof (Figure 1, step 1). Columns were created at the corners of the roof and a lofted surface was cre-

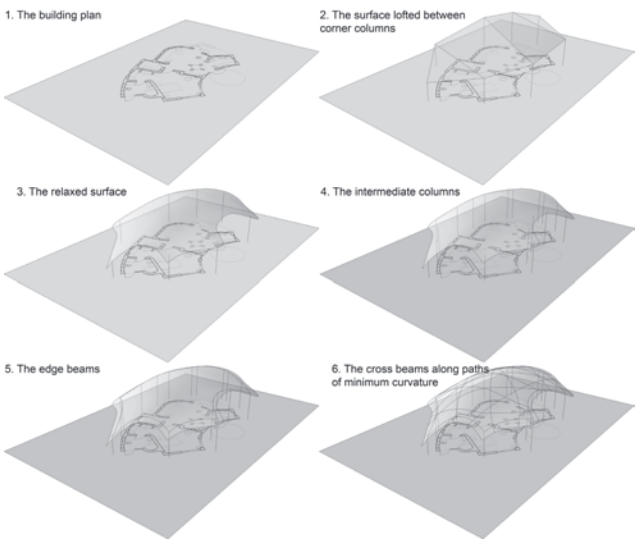

Figure 1. Steps in the design of the permanent formwork.

ated to span between the tops of the corner columns (Figure 1, step 2). A commonly available, open-source, surface-relaxation algorithm was customised for this project and used to create the funicular surface of the roof from the lofted surface (Figure 1, step 3). Further columns were added along the periphery of the funicular surface between the corner columns (Figure 1, step 4). Edge beams were then created by connecting the tops of the columns along the funicular surface (Figure 1, step 5).

7. Weaving as a Method to Create a Doubly Curved Permanent Formwork

Having determined the shape of the roof using the established form-finding methods, the next step was the design of the woven permanent formwork spanning across the edge beams. The process of weaving was chosen as a means to communicate the design to the craftspersons constructing the structure and enable them to construct the complex, doubly-curved reticulated shell in a manner that enabled its manual fabrication.

Weaving involves the laying of intersecting, flexible, linear members to create a form that may be a flat sheet (like a mat), or a singly or doubly curved surface (like a basket). It is the flexibility of the individual members held along a curve by their intersections with other members that allows the overall woven surface to curve. The relative positions of the intersections in space, and the lengths of the flexible members between the intersection points determine the curvature of the surface. The only measurements required to specify the doubly curved woven surface are the distances between intersection points along each member and the positions of the end points of the members.

For the following model (Figure 2), a doubly curved surface was constructed in a 3D modelling software (Figure 2, step 1) and iso-curves in two directions

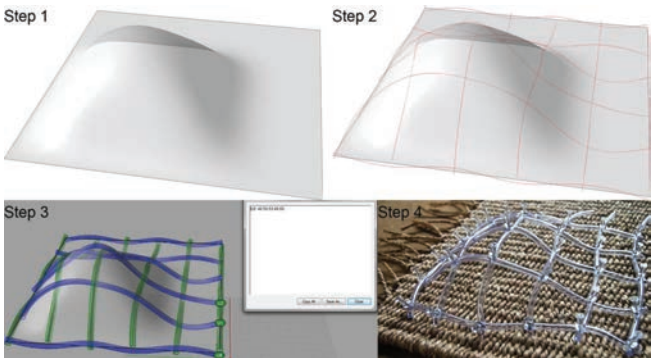

Figure 2. Weaving a doubly curved surface from a 3D digital model.

were drawn on the surface. The iso-curves were modified to take into account the thickness of the plastic tubing (Figure 2, step 2) and the lengths between intersection points were measured along each curve. A simple script was created to automate this process (Figure 2, step 3). The distances between intersection points along each curve were read off the digital model and marked along the tubing material. The resulting members were then woven by pinning intersecting tubes at the marked points to make the surface (Figure 2, step 4).

8. The Design of the Woven Permanent Formwork

The material chosen for weaving the permanent formwork for the roof was bamboo. The larger the diameter of a culm of bamboo, the stronger and less flexible it is. Iso-curves and regular grids mapped on to the funicular surface resulted in members with very great curvature which would have required very thin, and therefore very weak, bamboo to construct them, making the structure unfeasible.

An algorithm was therefore devised to find the path of minimal curvature through any given point along a surface. This algorithm was used to find paths of minimal curvature along the funicular surface passing through selected points on the edge beam (Figure 1, step 6). Weaving members along these paths of minimal curvature allowed the use of the strongest possible bamboo members with the largest diameter since the curvature required of the members is a minimal.

The single-line 3D model including the column centre lines, edge beam centre lines, and cross beam centre lines obtained from the paths of minimal curvature, was used to analyse the structural behaviour of the roof by ST.AR. Consulting Engineers. The results of the structural analysis determined that the average bamboo diameter required was 200mm with a wall thickness of 12.5mm, and that the edge beams and the cross beams along the paths of minimal curvature were required to be 600mm deep.

Based on some rudimentary physical tests on bamboo of the required specifications, it was found that half-round bamboo members would be able to achieve the curvatures required of the cross beams following the paths of minimal curvature along the surface. The edge beams, on the other hand, had been derived by connecting the tops of the columns along the funicular surface and were therefore not necessarily paths of minimal curvature. The greater curvatures required for the edge beams necessitated the use of quarter-round bamboo members for their construction. In order to achieve a beam depth of 600mm as specified by the structural analysis it was decided that the edge and cross beams would be built up with multiple layers of quarter-round and half-round members respectively. The weaving sequence for the roof (which determines which member goes over and which member goes under in an intersection) was then decided.

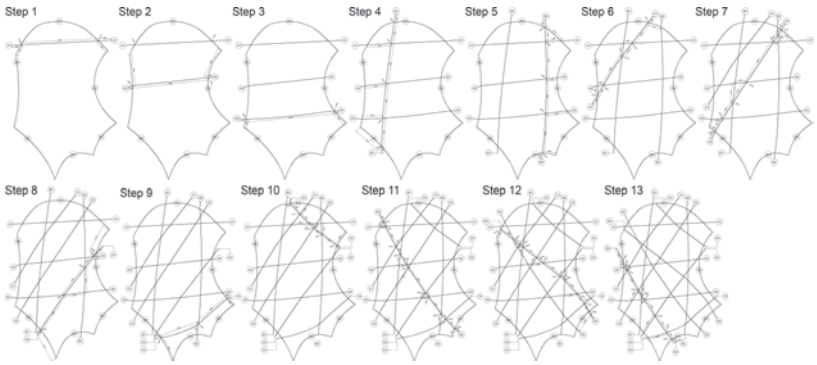

Figure 3. The construction drawing set.

Having determined the weaving sequence and the thicknesses of members required, this information was used to create a set of drawings for construction. The construction drawing set (Figure 3) consisted of a series of plans showing the sequence of construction based on the weaving sequence. Each drawing in the sequence provided the information needed to weave one member of the roof. The drawing gave the lengths between the intersection points along the member and whether the member would go over or under at each intersection point.

9. The Construction of a 1:25 Scale Model of the Formwork

Before embarking on the construction of the roof, a physical construction model at a scale of 1:25 was built (Figure 4). The purpose of building the construction model was to check if the information provided in the construction drawing set

Figure 4. The Construction model.

was sufficient to build the roof and if the craftspersons building the roof would be able to make use of this information as they worked. The construction model was built by members of the team that would eventually build the roof. The material chosen for the model was hand-split slivers of bamboo representing the half-round and quarter-round members of the roof. After being briefed on the project and the notations in the construction drawing set the craftspersons were able to successfully build the model.

10. The Construction of the Formwork

While following the linear dimensions given in the construction drawing set, the craftspersons (Figure 5) on the site were free to negotiate the unpredictable variations in the bamboo during construction.

For example, culms of bamboo that were thinner (but within the structural requirements) were used where greater curvature was required or where spans were smaller, and thicker culms were used for larger spans and members with lower curvature. Also, where members were longer than the longest length of bamboo available, two culms were joined at the nodes. At the points where the edge beams of the roof rest on the columns, bamboo spacers fill any gaps between the beam and column. Since the exact size of the bamboo can not be determined, the spacers have to be cut to fit each unique joint. Yet, following the linear dimensions provided in the construction drawing set enabled the craftspersons to build the formwork for the digitally designed doubly-curved surface.

The bamboo beams were woven, 20mm average diameter bamboo were laid out across the beams as reinforcement and permanent formwork for a 50mm thick layer of cement micro-concrete (Figure 6). The only steel reinforcement in this bamboo-crete roof spanning 19m X 12m will be a 16 gauge welded GI mesh with 25mm spacing which prevents the cracking of the micro-concrete.

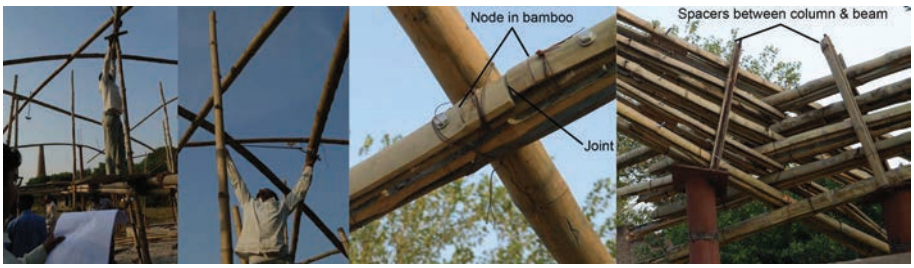

Figure 5. Reading linear measurements while negotiating variations in material.

Figure 6. The woven bamboo permanent formwork ready to receive the bamboo-crete.

11. Conclusion

While this methodology involves both designers and craftspersons, it is not simply the manual fabrication of a designed object. In this process a design informed by craft and material feeds back into a craft process and contributes what is impossible to achieve through craft alone – namely the form-finding of a complex, doubly curved surface, and paths of minimal curvature along this surface. The digital design process thus enables efficiency in the use of a non-industrial material that is impossible through a completely craft based process. The craft based construction was essential because a completely industrial or digitally driven process will not be able to negotiate the variations naturally present in a non-industrial material like bamboo. The importance of the craft based process can be seen by realising that if another roof were to be constructed using the same construction drawing set, it will not look the same because the bamboo members will be different and the way in which the craftspersons will negotiate these material variations will be different.

This methodology therefore opens up the advantages of digital design to those without the access to technologically intensive digital fabrication tools and expensive industrially processed materials, as well as opening up non-industrial materials to digital design processes.

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References

Bechthold, M.: 2004, Digital design and fabrication of surface structures, *Fabrication: Examining the Digital Practice of Architecture*, University of Waterloo School of Architecture, Cambridge, ON, 88–99.

Dutta, A.: 2007, *The bureaucracy of beauty: Design in the age of its global reproducibility*, Routledge, New York, 206–213.
Enns, J.: 2010, Intelligent wood assemblies: incorporating found geometry and natural material complexity, *in* Lydia Kallipoliti (ed.), *Architectural Design Special Issue: EcoRedux: Design Remedies for an Ailing Planet*, John Wiley, Malden, MA, 116–121.
Feibig, C.: 2011, "Computer Augmented Craft". Available from: The Machine <http://www.the-machine.be/en/designers/christian-fiebig/> (accessed 28 August 2012).Griffith, K. and Sass, L.: 2006, Computing & materializing non-uniform shapes: An evolutionary approach to generate and digitally fabricate non-uniform masonry walls, *CAADRIA 2006 [Proceedings of the 11th International Conference on Computer Aided Architectural Design Research in Asia]*, Kumamoto, Japan, 227–235.
Kamath, A. V.: 2009, Integrating digital design and fabrication and craft production, MSc Thesis, Massachusetts Institute of Technology, Cambridge, MA, 23–30.
Paoli, C.: 2007, Past and Future of Grid Shell Structures, MEng Thesis, Massachusetts Institute of Technology, Cambridge, MA, 13–14.
Pine, B. J.: 1999, *Mass customization: The new frontier in business competition*, Harvard Business School, Boston, MA.
Pye, D.: 1968, The nature and art of workmanship, Cambium, Bethel, CT.
Sennett, R.: 2008, *The craftsman*, Yale University, New Haven, CT.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 633–642. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

THE HAND AND THE MACHINE: A HYBRID APPROACH TO COMPLEX CONSTRUCTION IN A WORK OF SIR PETER COOK

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Abstract. This paper describes and provides a critique of the design and implementation of the "scoops" – a set of bespoke multifunctioning architectural free-form concrete elements that are a highlight of the new Soheil Abedian School of Architecture by the office of Sir Peter Cook and Gavin Robotham (CRAB). The development includes the transfer of analogue design processes into digital 3d modelling, which is then analysed and rationalized via an exchange with consultants and procurement contractors. The complexity of the concrete works necessitated the use of digital fabrication to make their implementation affordable and within time constraints, with said complexity creating a variety of challenges for many aspects of the entire delivery team. The 3d model played a critical role in communicating intent and accuracy at all stages. The use of site-based craftsmanship combined with computer aided design and fabrication overlapped to realize the project.

Keywords. In-situ concrete; 3d modelling; Rhinoceros; Peter Cook; digital fabrication.

1. Introduction

Architects and designers work in an age today where achieving formal complexity in their work is readily achievable via the spectrum of software platforms and modelling processes one can access in the studio environment. However taking complex formal qualities into the built world within budgetary constraints and quality standards is still often an experimental process and one imbued with risk. Pushing experimental work forward is critical for the discipline to advance (Beson, 2012), and through these instances, the procurement process is seen to evolve into more integrative means of collaboration and production between all parties in the building process (Kolarevic, 2011). Modelling software which

allows transference of information between disciplines – particularly across the chasm that often exists between parties focused upon design and those carrying out implementation – is key in enabling the integration required for novel and progressive advances in our spatial and material environment.

In December 2010, the office of Sir Peter Cook and Gavin Robotham, Cook Robotham Architecture Bureau Ltd ("CRAB Studio" London) won a two-stage, open competition to build a new faculty of architecture at Bond University, Gold Coast, Australia. The newest building on a campus originally designed by Arata Isozaki, the Soheil Abedian School of Architecture is a predominantly concrete building with bespoke glazing infill and a lightweight steel roof that will house 250 students upon completion in mid-2013, within a net area of 2500m2.

The building is a culmination of Cook and Robotham's position as both architects and as teachers at leading institutions globally. Informed by this academic experience, the project incorporates responses to many anecdotal criteria that are particular to architecture schools, as well as constructional and climatic objectives. The sociology of intimate groups within institutions, the value of casual overlay, and the importance of the non-curricula moments are all embedded in the project.[1] The primary physical embodiment of this attitude is featured in what is also of the most compelling aspects of the project: several four-storey tall in-situ concrete elements referred to by the designers as "scoops".

Carrying out a variety of programmatic roles, the "scoops" support the roof, act as a buttress for lateral loads, accommodate vertical circulation along their perimeters, function as ventilation chimneys, create a venue for design critiques, and also carry light down into the central recesses of the building (Figure 1).

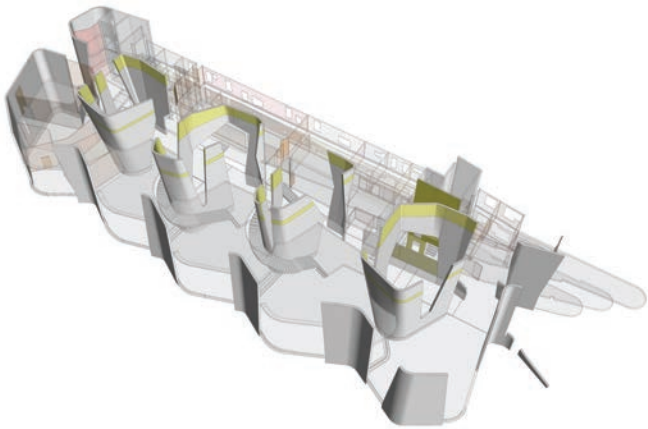

Figure 1. Isometric view showing the four "scoops" (CRAB).

Adding to this complexity is the formal resolution of the "scoops" themselves. These elements are customised in each instance although they share a common spatial and material quality in their totemic placement within the project's organisation. The "scoops" curve in plan, splay in multiple directions in section, are punctuated with multiple voids and structural connections, and in two instances, support cantilevered concrete stairways.

2. Design Process: Competition Stage

As is typical of Peter Cook's work, the project was initially developed using heuristic methods of sketching and physical modelling to develop and test the radical formal qualities of the project (Teyssot, 2010), and then was quickly developed through the use of McNeel Rhinoceros 3d (Rhino) and subsequently documented with Autodesk AutoCAD to hit immediate targets for Stage 1 of the competition phase. Conceptually, the "scoops" played a prominent role in how the project was conceived and represented in the early stage development of the project. Sketches by CRAB director Gavin Robotham indicate the interdependence of the "scoops" to anchor the scheme (Figure 2) and Peter Cook's sketches for the competition presentation cast the "scoops" as the backdrop for key narrative scenarios in the building.

Figure 2. "Scoop" conceptual development sketch (CRAB).

3. Design Process: Development and Validation Stage

As noted, every element of the building was designed in the CRAB office in Rhino. Rhino was used to create a variety of instances and virtual prototypes of

the scoops in the context of the overall design, and beyond the office, the Rhino model proved to become an essential element of the procurement documentation.

To implement the "scoops" and other in-situ concrete elements of the building, the Rhino geometry was given to ARUP Brisbane as a DWG file in conjunction with PDF drawings. Similar to the process of engaging Bernhard Franken for the Kunsthaus Graz as noted by Kloft (2003), the structural engineering phase did not put any design pressure on the project and was able to support the designer's intent fully, as the "scoops" are effectively normative load-bearing structures despite their geometric complexity. A principal challenge from a structural point of view was the accessibility of vibration equipment into the curving forms amongst the required density of reinforcing steel.

4. Implementation Process

The true challenges inherent in the concrete work became recognizable to the construction team only after the project works commenced. The project was carried out on a design/build contract, and as such, the contractor controlled and distributed all documentation including the 3d model in the form of a 3d PDF. The subcontract for the concrete work was awarded to a small but relatively experienced regionally-based firm. CRAB Studio had conceived that the concrete work would be cast using a combination of standard and custom-made steel formwork. However because very little of the geometry allowed for more than one pour, the contractor proposed site built plywood forms used in conjunction with limited reusable formwork. Within the first week of construction it was clear the complexity of the works would cause significant obstacles to achieve the necessary accuracy using conventional means of site carpentry. The contractor contacted international formwork supplier, PERI, to provide a possible solution. PERI Germany has previously implemented complex freeform geometry on the Mercedes Benz Museum, Stuttgart by UN Studio and projects by Santiago Calatrava, among others.

The 3d model proved to be the essential basis for communication of the exact intent and dimensionality of the desired building. Development of the formwork shop drawings was undertaken at PERI Germany and then transferred to PERI Brisbane for implementation locally, using the Rhino model as the key document.

5. Revised Process

PERI proposed a process used on previous freeform projects, namely, a system of "waffle slab" or notched plywood formwork with a curved plywood skin. This method, akin to developing cross-sectional prototypes, allows for the creation of

curved and raking surfaces on the pour side of the form, while maintaining a plumb and level face on the opposite side to which buttressing can be affixed during the pouring process. The notches in each perpendicular plywood rib enable site carpenters to easily and quickly jig the forms together with precision.

Initially, the PERI cost estimates for this method came in very high due to the number of customized forms. CRAB revisited the scoop geometry to introduce a greater degree of inter-changeability in the formwork geometry. This was handled rather intelligently to still achieve diversity and variation in the outcome, particularly by setting like formwork at different base angles in different scoops, for example.

The project was then re-evaluated and found to achieve the necessary cost reductions and thus a new strategy fixed into place for procurement. Each “scoop” in the project required 4 to 5 pours or lifts from top to bottom, with the average height between pours being 3.3m. In total, approximately 400 separate forms had to be installed with just under 50% of those forms being re-usable. As such, the customisation, tracking, and integration of the formwork needed to be highly detailed and organised. The forms themselves were fabricated from 18mm plywood and then surfaced with 6mm or 12mm plywood coated with polyurethane to achieve the required Class 1 finish.

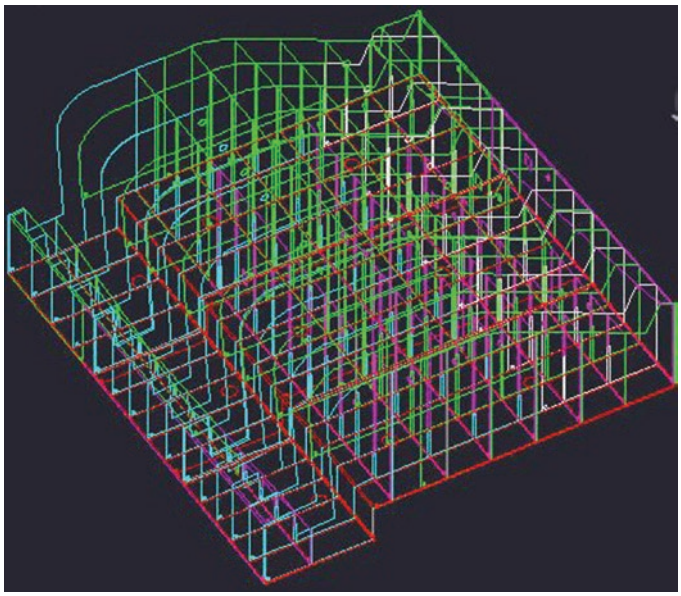

Figure 3. 3d Formwork shop drawing model (PERI).

PERI Germany developed the formwork shop drawings using AutoCAD 3d from CRAB's DWG file export. A manual technique requiring hundreds of instances of Boolean intersections were undertaken, and the ensuing drawings developed much like a drafting exercise as opposed to one of modelling. The need to establish a parametric model in this case, while perhaps obvious in retrospect, was not developed. It is important to point out the limited ability for collaboration to ensue between parties because of the construction contract.

Next in the process, PERI Germany sent to Brisbane a PDF A1 format shop drawing set detailing every element of custom formwork (again, more than 400 drawings, or approximately 100 per "scoop") and also a DWG file describing the waffle slab form as an un-nested, un-labelled 3d model view (Figure 3). The concrete contractor was responsible for unrolling and flattening all of the cut file geometry in AutoCAD and supplying it to the CNC fabrication subcontractor who then nested it, cut it, and sent it to site for assembly. This entire process of sorting and labelling the digital model was performed manually by CAD draftsmen for 2,400 plywood sheets.

6. Challenges and Results

A team of 35 formwork carpenters and labourers was required for on-site construction of the "scoops" and other concrete elements. While the concrete work was greatly aided by the supply of two-way gridded plywood formwork that was inherently self-jigging, many challenges still remained. Issues such as the varying radii, which required surfacing the formwork with different thicknesses of plywood in-situ, were one such challenge. Additionally, the PERI formwork indicated the location of tie-rods but the CNC milled formwork did not accommodate this in a conflict-free manner. Furthermore, the contingencies of on-site construction led to marginal but significant errors. Slight irregularities in the footings, for example, led to formwork being out of plumb, and thusly resulting in inaccurate connections to the next lift if they were not identified prior to the pour. Figures 4 and 5 shows a typical view of the construction site.

A surveying team assisted to verify locations of the formwork before all pours, and also to create as-built reference points after each pour to prepare for the next lift. The surveyor relied exclusively upon the CRAB 3d model, and similarly, subsequent trades in steel and glazing required these as-built drawings for their shop fabrication.

The engineering of the "scoops" required N-12 reinforcing steel at nominal 150mm and 300mm centres, encased by 40MPa concrete with 10mm aggregate and 100mm slump to ensure it wet enough to conform to the geometry without leaving voids or deformities. With all care taken, many irregularities, such as

Figure 4. Construction process on site (ADCO).

Figure 5. Construction process on site (photo by Author).

lipping or small voids, did however eventuate and grinding/patching was required. Furthermore the interchange of plywood form surfaces mixed with proprietary steel forms where they were able to be used, meant a large range of resulting surface qualities that required mitigation.

At the inception, the concrete work was anticipated to unfold over a 6 month period. Instead, the works lasted nearly 12 months. While the prefabricated forms ameliorated the complexity of the project, the nature of the project was inherently difficult. While the building team proved up for the challenge, it was also a process that was entirely novel for most involved and thusly proved to be a very slow process and one which was costly. In the end, the work was very successful given the overall quality and powerful formal qualities of the architecture.

7. Conclusions

The conception and implementation of the complex concrete work in the form of the "scoops" at the Soheil Abedian School of Architecture represent a hybrid formation of both analogue and digital methodology, and offer a demonstration in the finished product of how these overlapping approaches integrate successfully (Figure 6). As a kind of spontaneous yet carefully controlled experiment, the team members involved were forced to innovate with the available digital tools and analogue methods available, and as previously suggested, one can identify areas in which the process could be improved or enhanced.

Compared to precedents for concrete construction in Australia, the work described here exceeded the experience of most members of the site team and required a tremendous leap in their pursuit of the required product. While PERI had previous off-shore experience with developing the requisite sophisticated formwork via CAD/CAM technology, the information flow was constrained, with no mechanism for feedback to influence subsequent rounds in the process. As such, the handcraft aspect of the process played an important role in closing the gap at the end of the digital workflow. Works of similar complexity such as Ito's Fukuoka Island Park or Kakamigahara Crematorium (Satsaki, 2008) demonstrate difficulties resolved by modelling, digital fabrication, and site-intensive craftsmanship, but it is even in these instances the concrete work was not cast into formwork.

Figure 6. "Scoops" nearing completion – February 2013 (photos by author).

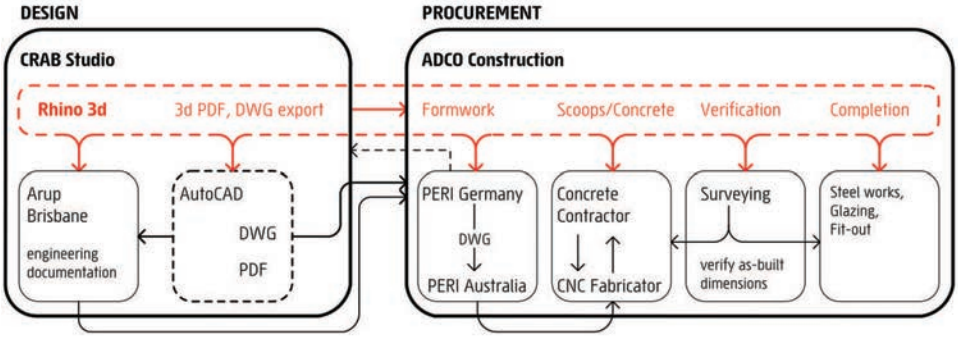

Figure 7. Workflow emanating from CRAB 3d model (by author).

Regarding information flow, this project offered a prime opportunity to apply an integrated project delivery method and the appropriate technological platform to support it. A standard design/build contract creates a segregated process, inherently bisecting the workflow into a "before and after" sequence relative to awarding the tender as indicated in Figure 7. Projects with elevated levels of complexity require an input and feedback loop between builder and designer to allow refinement and sharing of expertise. The Australian "Alliance" contract, or North American "Integrated Project Delivery," would allow the type of non-standard protocol required (Williams et al., 2011). Even though the Rhino model allowed for information flow and for CRAB to maintain review of conflicts, the contractual apparatus used inhibited this review. CRAB made a very determined effort to share their intent via Rhino, but the platform does not support dynamic collaboration as would BIM platforms such as Digital Project (Beorkrem, 2013, pp. 11–12).

The formwork engineering and fabrication could have been improved and streamlined. The manual process of developing section profiles, labelling, and nesting of the individual plywood forms is a process which using Grasshopper, for example, could have been automated and compressed tremendously. Such a strategy would have easily integrated with CRAB's preferred platform and allowed for parametric updating of all 2,400 cut files at the stage when the "scoop" geometry was rationalized. Combined with the appropriate contractual apparatus, CRAB could have occupied a central role with the "scoop" construction, offering an example of architect-as-master of this craft intensive process (Klinger, 2008). The contract applied to the project inhibited CRAB's ability to communicate effectively once such problems and opportunities were identified. The engagement by the contractor of suitably experienced and skilled consultant could have aided the process by providing parametric maintenance of documentation. Few

consultancies, such as designtoproduction or CASE, presently exist but they represent an emerging professional model for the discipline. In Australia, the firm AR-MA (Sydney) represents one such entity that could provide the required digital facilitation.

An exemplary outcome in complex concrete construction that all members of the process are rightfully proud, the "scoops" at the Soheil Abedian School of Architecture provide a valuable example of progress in the capacity of the Australian construction industry. The assessment and review of this process can hopefully serve to inform future endeavours of similar or advanced complexity, which are an imperative for industry growth. This project signals the need for tighter collaboration, effective contractual integration, and the need for appropriate digital technology to support efficacious delivery in a dynamic process with complex formal and spatial objectives.

Endnotes

1. http://www.crab-studio.com/bond-university/ (07-02-2013)

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References

Beson, R.: 2012, The case for customisation, *Architecture Australia*, **101**(5), 78–79.

Beorkrem, C.: 2013, *Material strategies in digital fabrication*, Routledge, New York.

Kloft, H.: 2003, Engineering of freeform structures, *in* R. Corser (ed.), *Fabricating architecture: selected readings in digital design and manufacturing*, Princeton Architectural Press, New York, 110–127.

Klinger, K. R.: 2008, Relations: information exchange in designing and making architecture, *in* K. R. Klinger and B. Kolarevic (eds), *Manufacturing material effects: rethinking design and making in architecture*, Routledge, New York, 25–36.

Kolarevic, B.: 2011, Toward computationally aided integrative design, *in* J. M. Taron, V. Parlac, B. Kolarevic and J. S. Johnson (eds.), *Proceedings of the 31st annual conference of the association for computer aided design in architecture*, ACADIA, 30–33.

Satsaki, M.: 2008, Morphogenesis of flux structure, *From control to design: Parametric/Algorithmic Architecture*, Actar, Barcelona, 68–115.

Teyssot, G.: 2011, In the shade of algorithms, *in* A. Santer and A. Lepik (eds.), *J. Mayer H. Metropol Parasol*, Hatje Cantz, Ostfildern, 77–83.

Williams, N., Stehling, H., Scheurer, F., Oesterle, S., Kohler, M. and Gramazio, F.: 2011, A case study of a collaborative digital workflow in the design and production of formwork for 'non-standard' concrete structures, *International Journal of Architectural Computing*, **9**(3), 223–240.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 643–653. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

A FLEXIBLE AUTOMATED DIGITAL DESIGN FOR PRODUCTION WORKFLOW

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Abstract. This paper documents the flexible automated digital design for production workflow utilized for the materialization of the FabPod Project, together with the use of an integrated practice methodology and highly collaborative process. The research seeks to narrow the divide between the acts of designing and the acts of making, by integrating through the act of automating computer assisted designs with computer assisted manufacturing.

Keywords. Automated design to fabrication workflow; integrated practice; CAD/CAM; parametric modelling; flexible modelling.

1. Introduction

We will be reporting on the specifications of a Flexible Automated Digital Design for Production Workflow (FADPW) shown in Figure 1, developed in Catia™ for the management of geometry control and tolerant modelling of the detailed fabrication planning data for the FabPod project. The Fabpod project is the second prototype produced as a continuation of the physical prototyping research developed during the Responsive Acoustic Surfaces cluster in SmartGeometry 2011, the work extends the understanding of how to manufacture Hyperbolic geometries and their complex intersection patterns through the integration of Computer Aided Design technology with Computer Aided Manufacturing technologies (Burry et al., 2011).

The Flexible Automated Design for Production Workflow system was a necessary step in the materialization of the FabPod design intentions. The system enabled the flexible orchestration of change management in the earlier stages of design and in the stages of fabrication planning.

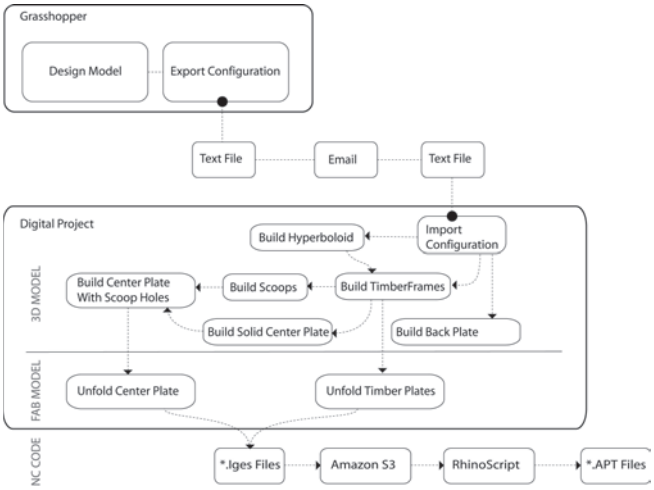

Figure 1. Workflow Diagram.

The FADPW deployed a novel use of a declarative simple geometry codex as the lingua franca for the exchange of information. This open exchange provided the design team with a decentralized collaborative environment.

2. Background

The FADPW system developed for the FabPod is the result of an accumulation of a research stream investigating how automation strategies enable the integration of design information with fabrication information by means of automating digitally mediated representations and translating them into accurate machining features for the extraction of multiple axis machining data.

As suggested by Mitchell and McCullough (1994, pp. 417-440) “Integrating computer-aided design with computer-aided fabrication and construction [...] fundamentally redefines the relationship between designing and producing. […]”

The integration of designing with manufacturing excludes the need for the mediation produced by drawings, With the integration of CAD with CAM we can achieve higher levels of systematized customization (mass-customization) “bringing the benefits of factory production to the creation of a unique component or series of similar elements differentiated through digitally controlled variation” (Kvan and Kolarevic, 2002). In addition this digitally controlled variation can be achieved with levels of accuracy and precision not attainable through traditional means of construction or fabrication. Kolarevic (2001), Maher and Burry (2006) and Shelden (2002) argue that to simply substitute 3D models for drawings will

not automatically guarantee a greater coherence of information, this suggests that while 3d model-based strategies can capture a greater breath of information, there are intrinsic properties to 3d model-based methods that if correctly employed, have a greater chance of guaranteeing coherence of information when compared to more traditional drawing media, for example the inclusion of automation strategies in combination with 3d model-based methods can provide a greater level of coherence among disparate components of a model without compromising the design-logic.

The revisiting of the design for manufacturing and assembly of products by the automotive, aerospace and shipbuilding industries during the ‘80s and ‘90s, demonstrated the use of integration strategies in combination with CAD/CAM technologies, and how their synergy enhances the effectiveness of the planning and manufacturing process (Kieran and Timberlake, 2004).

While the benefits of integration mediated through technology have been widely acknowledged by the AEC community, the process of adoption has been slow. In an industry built on the separation of design, construction and project phases, many integrators are having a hard time implementing collaboration and concurrence (Elvin, 2010).

As noted by Hartmann et al. (2008) professionals find it difficult to cope with ways of effectively integrating model-based strategies into normative practice, coupled with a lack of understanding of the digital modelling process and of the digital fabrication process. (Hartmann et al., 2008; Chaszar and Glymph, 2003) While practices such as Gehry Partners have been adopting these methodologies and principles since the 1990s such as their collaboration with the Metal Fabricator Zahner during the construction of the Music Experience Project in Seattle, the observations made by the researchers above help identify a clear gap in our knowledge base, in particular in effective methods of integrating design information with fabrication information, coming from multiple sources of expertise and in a variety of representations.

The main proposition of this paper is that automated design for fabrication work-flows have enormous potential to eradicate the barriers presented by both the separation of the design and fabrication process and the difficulty professionals face when implementing an effective integration of model-based strategy within normative practice.

In response to the observations made by the key researchers within the literature, we conceived the FADPW system to research the potential in application of automated workflows to narrow the divide between the acts of designing and the acts of making. It would do this by integrating through the act of automating computer assisted designs with computer assisted manufacturing. Can the restructuring of the acts of materializing architecture enable us to re-institutionalize the seamless collaborative enterprise that was once encapsulated by the role of the “Master builder”? (Kolarevic, 2001).

3. The Workflow System

3.1. CONCEPTUAL FRAMEWORKS VS PHYSICAL FRAMEWORKS

In *Refabricating Architecture*, Kieran and Timberlake (2004) introduce us to the different "ways-of-making" used by the automotive and Aerospace industry, the differences between the industries are vast, they see the differences as one of "framing" vs. "quilting". Framing is seen as "entirely gravity based" and bound to a precondition of physical existence, quilting on the other hand is seen as requiring "only a conceptual, not a physical framework." That is, physical frameworks force the process to be linear and make the assembly process highly dependent on gravity, for this reason in "framing" the assembly process must begin from the ground-up starting with the construction of a "frame", which behaves as a primary support system; after the "frame" is built, the components that hang from the frame follow.

The "framing" exposes an overseen characteristic of the relation between the ways in which we organize information and the ways in which we fabricate and assemble components from that information, for example the "conceptual framework" enables a non-linear fabrication and assembly process, where components can be fabricated, assembled and joined to their adjacent neighbours, without gravity acting as the primary regulating line in the order of the system. Instead in the "conceptual framework" it is information that becomes the regulating line of the system, the informational system enables us to manage the interfacing joints between components, in a process similar to how "quilts" work, the informational "patches" which subsequently become fabrication cells can be built out-of-order and stitched together after shipped to the assembly site.

During the Fabpod, the Automation Workflow became the informational backbone of the "conceptual framework" enabling a "quilt-like" process of fabrication and assembly.

3.2. THE GRASSHOPPER AUTOMATION

In the FabPod project, Rhino/Grasshopper was used as a design authoring tool, where the wall and cell assemblies would be declared and specified according to a highly flexible set of design principles and functional requirements for room acoustics. While fundamental to the design process, the workflow in Grasshopper software is outside the scope of this paper.

3.3. THE DIGITAL PROJECT AUTOMATION WORKFLOW

The Flexible Automation Digital Project Workflow system enabled the re-generation of fabrication-geometry control models reconfigured according to strict yet robust fabrication conformance guidelines.

The looseness of the Grasshopper automated workflow in allowing design changes and the robustness in the Digital Project-based automated workflow with its ability to incorporate design changes while strictly conforming to the fabrication rules and manufacturing guidelines, highlights the great potential of automated workflows in enabling the integration of flexibility in design while maintaining robustness at the fabrication level.

3.4. THE FILE TRANSFER PROCEDURE AND COLLABORATION

The simple file format developed for the interoperability between the two automation workflows, required the necessary conditions indicated by Kvan (2000) for the production of a loose-coupled collaborative process, furthermore Maher and Burry (2006) in their definition of the "exclusive" collaboration type, define it as a process where by each participant "work[s] on separate parts of the problem, negotiating occasionally by asking advice from the other."

The use of the simple file format facilitated a high degree of collaboration, the process was also mediated through email exchanges providing a basic level of coordination between the design team and the fabrication planning team.

The simple file format relied on the assumption that mathematically defined constructs, such as planes, points and lines have stable characteristics.

These constructs could then be transferred using our simple text-based file format from Grasshopper (where the acts of designing where being made) into Digital Project (where the acts of detailed fabrication planning where being made) with the assumption that the mathematically defined objects in Grasshopper would have the same stable characteristics in Digital Project.

These constructs would be transferred out of Grasshopper through automated routines, and the exported constructs would be transferred into digital process through an automated routine as well, as such automation was seen as the key integration device throughout the project in contrast to relying on standardized file formats or manual intermediation.

3.5. MACHINE FEATURES AND USER DEFINED FEATURES

CNC machinery require considerable efforts and expertise in the planning and operating of machinery, machining is not considered a Rapid Prototyping (RP) tool.

In computer aided manufacturing (CAM) and CAD/CAM integration, machining is automated, and computer aided design is integrated into the machining process. "Machining features" have become widely adopted by designers, assisting in the conversion of design intent information into machining instructions. (Balasubramaniam et al., 2000) While acknowledging the convenience of this form of representation, Balasubramaniam et al. (2000) also warn about the disadvantages

of the “machining feature” approach, they point out that feature-based systems are limited by the extent of their semantic vocabulary.

Although requiring an added level of expertise, the limitations highlighted by Balasubramaniam et al. (2000) are circumvented by the use of “user-defined-features”, that is, features created by the user, as opposed to features packaged with the software, this is where systems such as Digital Project based on CATIA surpass other systems that don’t provide users with such a degree of customization.

By automating the production of accurate detailed planning data for machining purposes much of the considerable labour involved in the machining process is eliminated, enabling the NC machining process to function similar to other RP technologies.

3.6. A ROBUST FEATURE BASED SYSTEM

According to Karam and Kleismit (2003) “Building flexibility into a model is, for example, critical in facilitating downstream engineering changes” further in facilitating downstream changes designers must address the “ability to anticipate the requirements of potential change [and acknowledge that this ability] is built on experience, training, and a natural intuition on how the design may have to be modified.”

Following the downstream considerations identified by Karam and Kleismit (2003), the FabPod “Fabrication Cell” Features were developed in isolation, ahead of the automation system that would subsequently glue them together into a seamless assembly. The rationale for taking such a counterintuitive decision, stems from the idea, that, in the event that the fully automated system would fail, there would still be the ability to instantiate the components manually, albeit with a considerable time penalty.

3.7. A DECOUPLED AUTOMATED PROCESS

As mentioned earlier in the robust feature section, the separation of the feature design from the design-logic automation was paramount and mission critical in enabling the flexibility goals stated earlier.

Figure 2 shows the differences between three prominent flexibility strategies, the “hybrid” approach combines computer code with traditional parametric models, the “pure code” approach relies exclusively on computer code as the method of representing the design intent and lastly the “pure parametric” approach relies exclusively on traditional parametric models for representing the design intent. Of these three approaches of representing the design intent, the “hybrid” approach has the greatest level of flexibility as a holistic process, since the responsibility of mapping the design-logic is shared across the scripter and end-user designer, the “pure code” approach places the burden of responsibility solely on the scripter and

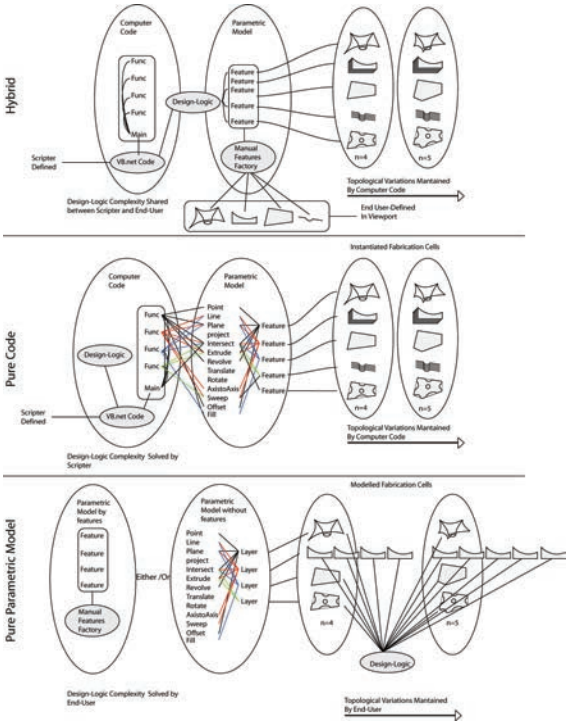

Figure 2. Flexibility Strategies.

isolates the end-user designer from the decision making, and finally the "pure parametric" model while relatively flexible its inability to vary topologically makes the end-user do all the heavy weight lifting in maintaining the design-logic as a manual and time onerous process.

The "hybrid" approach enables to decouple architectural geometry problems (tectonics), from computer programming problems (logics). with this method, professionals working on complex shaped and articulated projects can effectively solve geometrical issues in 3d using visual methods natural to the process of design, while the computer programming component that *instantiates* the three dimensional features can be debugged using traditional text-based debugging methods.

Another benefit of the decoupling of the tectonic issues from the logic issues, is the ability for "scripters" to collaborate with other team members who do not have automation skills "end-user designers". Participants with sufficient parametric model-based knowledge can contribute in the building of the smart features required, while another participant with knowledge in automation can deal exclusively with the mapping of the design-logic through computer code.

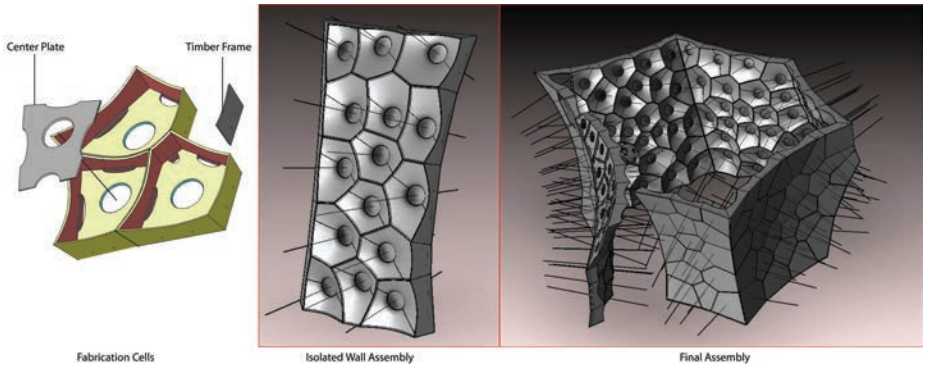

Figure 3. Fabrication Cells and Wall Assemblies.

3.8. THE TECTONIC ISSUES

Due to issues of space we will only cover the tectonic characteristics of the two most difficult features in the project.

3.8.1. The Timber Frames

The assembly requirements of the timber framing system challenged the use of a traditional parametric modelling strategy. Although parametric modelling systems such as Digital Project enable designers to map design intent as flexible models, these associative modelling paradigms present a great deal of difficulty in coping with topological variations. For this reason in the FabPod project, we implemented the "hybrid" approach as illustrated in Figure 2 in contrast to other methods, the "hybrid" approach enabled the flexibility required in varying the number of total frames per fabrication cell, the number of sides in the frame data was variable, the numbers fluctuated based on the design data arriving from the Grasshopper Voronoi distributions over spherical surfaces. While traditional parametric modellers do not facilitate topological variations without computer code in their off-the-shelf modalities, the "hybrid" strategy is a best of both worlds solution, enabling the end-users to articulate the smart features and the scripters to define the topological variation inherent in most algorithmic design-logic processes.

With the separation of the tectonic issues from the logic issues using feature-based components, it was easy to manage the geometrical complexity required without this complexity getting entangled with the complexity of the design-logic.

3.8.2. The Center Plate

The dependency of the centre-plate stiffener on the variable number of timber frames and scoop holes respectively, highlighted the necessity of having a flexible strategy for orchestrating this kind of topological variation. The dependencies on the timber frame topology affected the number of scoop holes, the scoop holes facilitated human hands in gaining access to bolts during the fastening process. Lastly, the centre plate feature was trimmed by the hyperboloid front-face and the timber frames at a variable angle non-orthogonal to the sheet plane, this would imply a 5-axis machining process for manufacturing, through end-user-defined "Machining features" simple geometrical representations translated seamlessly into 5 axis machining data.

3.8.3. Unfolding the Geometry into Sheet Space

The last Component of the FADPW system was the translation of the 3d assemblies into unfolded nested components for easy NC data extraction.

Using Digital Project's axis-to-axis transformations and coupled with computer programming logic, the process was automated effectively and all the unfolded data was transferred into the last process converting the unfolded control-geometry into Automatically Programmed Tool (APT) data, this step was developed outside of Digital Project in Rhinoscript, as an alternative to the use of Dassault DELMIA for the production of tool paths.

4. Conclusions

The research described in this paper investigated the topic of flexibility and integration as it applies to 3d model-based design for manufacturing and assembly. We discussed the various factors affecting flexibility, these ranged from the need of a vendor-independent 3d model-based framework that promotes open collaboration and the integration of information from various sources, to the disentanglement of geometrical complexity from design-logic complexity to facilitate a more visual process of interacting with tectonic issues and the need for topological variability in traditional parametric modelling paradigms.

The paper briefly illustrated the collaborative potentials of text-based neutral-file interoperability and how this form of interoperability promotes flexibility, as information can be exchanged and aggregated from multiple sources with a high degree of fidelity and an open file structure.

In future research it would become advantageous to develop more active strategies for respecting geometrical consistencies avoiding passive methods such as clash detection and post-instantiation validity checks, a greater understanding of

the use of "Embedded Rationality" could improve the quality in the design of machine assisted manufactured objects. Future efforts will be directed in a more detailed qualitative/quantitative assessment of the impact of automation in enabling flexibility for the delivery of non-standard projects with a high degree of geometrical complexity.

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References

Balasubramaniam, M., Laxmiprasad, P., Sarma, S. and Shaikh, Z.: 2000, Generating 5-axis NC roughing paths directly from a tessellated representation, *Computer-Aided Design*, **32**, 261–277.

Burry, J., Davis, D., Peters, B. Ayres, P., Klein, J. Pena De Leon, A. and Burry. M.: 2011, Modelling Hyperboloid Sound Scattering: The Challenge of Simulating, Fabricating and Measuring, in C. Gengnagel, A. Kilian, N. Palz, F. Scheurer (eds.), *Computational Design Modelling: Proceedings of the Design Modelling Symposium Berlin 2011*, Springer.

Chaszar, A. and Glymph, J. 2003. CAD/CAM in the business of architecture, engineering and construction, *Architectural Design*, **166**, 117–123.

Elvin, G.: 2007, *Integrated practice in architecture: Mastering design-build, fast-track, and building information modelling*, John Wiley.

Hartmann, T., Gao, J. and Fischer, M.: 2008, Areas of application for 3D and 4D models on construction projects, *Journal of Construction Engineering and Management*, **134**, 776–785

Karam, F. and Kleismit, C. D.: 2003, Using Catia V5, OnWord.

Kieran, S. and Timberlake, J.: 2004, *Refabricating architecture*, McGraw-Hill, New York.

Kolarevic, B.: 2001, Digital Fabrication: Manufacturing Architecture in the Information Age, *Reinventing the Discourse-How Digital Tools Help Bridge and Transform Research, Education and Practice in Architecture*, Association for Computer Aided Design in Architecture, Buffalo, NY, 268–278.

Kvan, T. and Kolarevic, B.: 2002, Rapid prototyping and its application in architectural design, *Automation in Construction*, **11**, 277–278.

Kvan, T.: 2000, Collaborative design: what is it?, *Automation in Construction*, **9**, 409–415.

Maher, A. and Burry, J.: 2006, The Re-Engineering Project Developing Pedagogical Frameworks for Early Stage Collaborative Design between Engineers and Architects, *in* G. A. Luhan (ed.), *Synthetic Landscapes: ACADIA 2006 International Conference Proceedings*, Association for Computer Aided Design in Architecture, 200–212.

Mitchell, W. and McCullough, M.: 1994, *Digital Design Media*, 2nd ed,, John Wiley.

Pine, B. J. II: 1993, *Mass customization: New Frontiers in Business Competition*, Harvard Business School.

Shelden, D.: 2002, Digital Surface Representation and the Constructability of Gehry's Architecture, PhD Dissertation, Massachusetts Institute of Technology, Cambridge, MA.

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FULL SCALE PROTOTYPING

Logistic and construction challenges realising digitally designed timber prototypes

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Abstract. This paper reports on the final stage of a research project with the realization of a real scale prototype and ties an empirical finale to the project, which started as a fundamental research project three years ago. The scope of this research project was to explore new ways, how Non-Standard Architecture can be build with standard building elements using contemporary building processes and materials resource efficiently. Mass Customization and File to Factory, concepts where a continuous digital workflow is applied, were fundamental to our approach. Within this framework we developed generic parametric details and made them part of the whole process from the beginning of the design to the manufacturing. The present paper describes a strategy for the assembly of a large prototype, consisting of approximately 50 flat timber panels that are being assembled to a structure of the size of a small house. The paper focuses especially on the customized falsework, we designed for the construction of the prototype, which became a crucial part of the assembling process besides the assembly of the actual prototype.

Keywords. Digital fabrication and construction; precedence and prototypes; mass customization.

1. Introduction

As we can repeatedly observe in digital workflows, the integration of the digital model throughout the design process is not a problem but when the structure becomes physical the problems manifold. As many architects have already experienced, we know how much manual work is required for (after) a digital

production (Scheurer, 2009). We will address major issues, dealing with the physical assembly of a full-scale prototype (approx. 4 x 4 x 10 m) of a freeform structure assembled from flat cross-laminated timber (CLT) panels. The falsework, which is required for the assembly, has to be as accurate as the structure itself. The job of this falsework is to secure each panel's position during the assembly process and must not allow movements in any direction.

In this paper we will discuss the experiences, we collected during the assembly process of the prototype with the focus on construction and logistic conditioned problems, which arise from the physical assembly of a prototype structure in building scale using a new gluing technique (Schimek et al., 2011) (Figure 1).

According to the concept of mass customization, we experienced a very smooth workflow through the whole production process of the parts with a five-axis router, but from our experience as architects we know, that the precession of digitally machined parts cannot be maintained throughout the whole construction process, especially when it comes to manual assembly. It seemed to be interesting to what extent we can perform a precise assembly using rather heavy parts. At the preparation of the panels for the assembly process, we tried to exclude potential error sources. Complications we expected predominantly from the logistic handling of the falsework and the panels of the prototype structure. How would we secure a fluid assembly process avoiding the single parts from blocking each other and respectively create enough free space for the tools.

To discretize the freeform design of the prototype we developed a customized algorithm (Manahl, 2012). Consequently helpful was an accurate 3D-model in

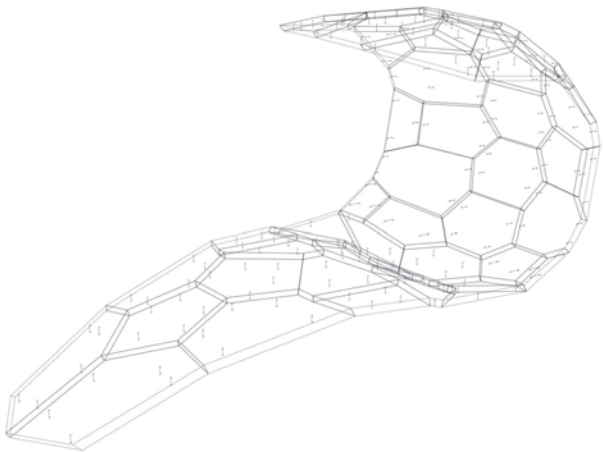

Figure 1. Prototype structure; Wireframe model of the panels. (IAM, 2012)

RHINOCERUS, where we could simulate almost every possible geometrical situation that could occur with the assembly (Calderon et al., 2011).

After eliminating most difficulties in the digital realm, we met with the craftsmen to discuss our theoretical approach. We incorporated their advices in our considerations before we started the assembly. Questions that are covered in this paper involve:

- How does the falsework fit the needs of positioning and securing the parts of the final prototype structure during the gluing process?
- Does the assembly strategy, e.g. the assembly order of the panels work in terms of the malleability of the structure.
- How can imprecisions, arising from the relatively large number of unique parts be addressed?
- How does the installation of the connectors work without interfering with the falsework?
- How can we avoid at the manual assembly (gluing) of the panels, that imprecision is reproduced through the structure with each part being added (error burst).

We were not able to draw upon experiences of former structures – for the time being no such self-supported timber structure exists. But looking at the sheeting of complex concrete structures, we can observe similar construction methodologies. At the Rolex Learning Centre in Lausanne by SANAA (Figure 2), Design-to-production, a Swiss based company, that provides services in realizing non-standard architecture, developed a specific formwork solution for the large, double curved concrete slab. The curved surface was built, using standard steel scaffolding components, with some 1,500 individual wooden boxes. Like in our project, DPD had to deal with the same problem statement: How to keep construction elements in a defined and secured position (DPD, 2008).

Figure 2. Left: Wooden boxes on standard scaffold. Right: General View. (DPD, 2008)

2. Structural Analysis

The structural calculation was performed on the FE-software ABAQUS. Load cases covered self-weight and wind blowing longitudinal to the structure. The structure is symmetrical to the centre line. The calculation led to a total number of connectors of approximately 300 (Pfaller, 2012). As foundation for the temporary prototype structure served a steel frame that was simply laid out on a gravel bed (Figure 3).

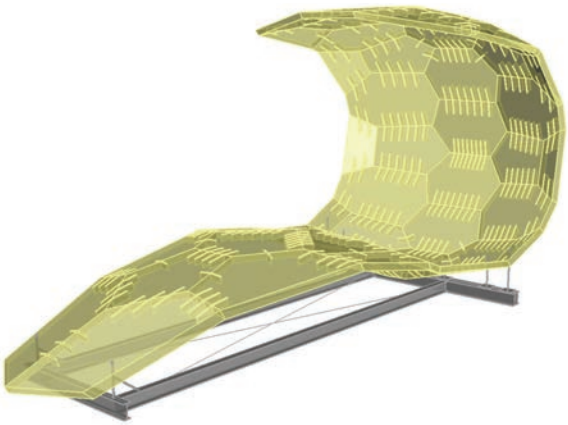

Figure 3. Prototype with connectors mounted on the steel frame (IAM, 2012).

3. Falsework

The major requirement for the falsework was to build a structure, which is capable of supporting the single panels point wise during the whole assembly process. The falsework also had to secure the position of the panels. Therefore the profile of the supporting elements had to be quite strong in order to be stiff enough. We decided to use single columns with a footprint of 100 x 100 mm based on the calculation of the structural engineers. The falsework columns were mounted on a grid of horizontal beams of the same dimension. The required precision of the falsework columns must not be different from the supported panels one.

In order to minimize an error burst through manual imperfections we decided to split the prototype for the final assembly on site into three modules A, B and C (Figure 4).

The panels of the prototype were temporarily fixed to the falsework columns by customized steel bolts and heavy screws. With the insertion of the bolts, the panels were aligned to the right position. For the alignment and as mounting fix-

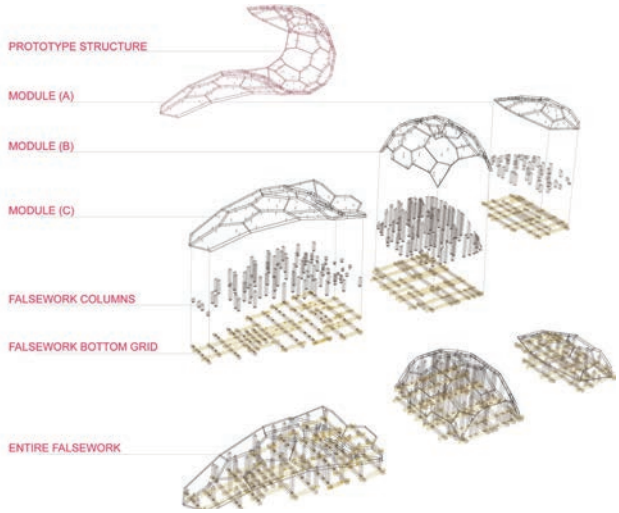

Figure 4. Topology of the assembly (IAM, 2012).

Figure 5. Left: close up of falsework. Right: Labelled falsework columns. (IAM, 2012)

ture for the falsework columns, we inserted two boreholes in diagonal order in the bottom of each column. The differently angled column topsides also received a centred borehole to hold the steel bolts.

Both, the vertical falsework columns and the laying grid were milled on a 5-axis router using a saw blade for the customized angles and a standard drill for the boreholes and slots.

After the milling process we had 275 parts in total, 191 upright columns and 84 horizontal beams that all looked quite similar (Figure 4, 5). Thus the labelling of the parts was crucial for the logistic handling of the parts. The labels indicated,

together with two diagonal arranged bores, the alignment of the columns with the underlying grid (Figure 5).

4. Digital Precision vs. Manual Imprecision

Using a five-axis router we experienced that the precision of the digitally fabricated parts were very satisfying, both, of the falsework parts and the panels for the prototype structure itself. The slots for the connectors could be produced within the required range of tolerance, which required a maximum gap width of 0,3 mm between the connector and the panel's slot. Working with such precision is certainly not common in the carpentry business on site and can only be achieved under factory conditions (Schimek et al., 2011).

The very smooth digital workflow at the fabrication of the parts proofed the qualification of a digital work chain, not a single plan was printed for the production and we directly provided Rhino's geometry to the workshop, where the code for the router was created. This reduced possible errors at the interface between the design and production. Using an integrated digital 3D-model, potential imperfections and errors could be identified in a very early stage.

We knew that this precise mode of operation could not be continued in the consequent manual assembly process. As mentioned before, we split the prototype into three modules (A, B and C). In a first stage we assembled the three modules separately in the workshop from the digitally fabricated falsework parts, then mounted the panels on top of it. Under factory condition we got much better results than we could expect on the building site. In a second stage we brought the modules to the assembly site and joined the modules on the prepared steel frame. This turned out to be the right decision since both, the pre-assembly of the modules and the following installation on site worked properly.

Unlike the digital process including the fabrication of the parts, where no paper drawings were required, the following manual assembly, which we performed in two steps (module assembly and final assembly) required the full physical information transfer with section, elevation, perspective drawings and a physical model in order to communicate the desired result to the craftsmen (Figure 6).

After all the craftsmen mainly used our 1:20 cardboard model of the complex surface, which communicated the freeform in a much better way.

5. Assembly Strategy

The automotive industry has replaced the production methodology of singular craft in the twenties of the last century through the assembly line and some eighty years later through modular production, whereas the production of architecture

Figure 6. Left: clipping of working drawing falsework module (B). Right: Panels mounted on falsework module (C), view from underneath (IAM, 2012).

still relies on the singular craft method, when it comes to complex buildings. In modular production sub-contractors built large chunks of a vehicle. At the end of the chain an original equipment manufacturer (OEM) finally puts together all the sub-assemblies to one piece. Sub-assemblies can be built simultaneously and the quality control of the single modules is much better. That makes the method of modular production very efficient, both, in terms of quality and cost. Additionally it reduces the error rate due to the fact that joining just a few pre-assemblies to the final assembly on site is less “dangerous” than putting together the whole piece from scratch (Kieran and Timberlake, 2004).

Working in building scale, using pre-assemblies also means to be aware of the scale of the single modules since there is a limitation of size when being transported on public roads. Therefore the sub-division of the prototype into three modules was strongly driven by these constraints. Without this limitation we would have assembled the whole prototype in one piece in the workshop.

A new gluing system, which was developed together with the structural engineers, used hard wood connectors that were inserted in the digitally fabricated slots. To meet the requirements of the one-component-polyurethane glue, which we used for the joints, the geometry of the slots had to be very accurate, leaving a maximum width gap of 0,3 mm between the hard wood connector and the slot. Consequently we had to angle the flanks of the slots conically. In doing so, we secured a very tight fit of the connector when it was inserted. A closer description of this process can be found in a former publication (Schimek et al., 2011).

5.1. MODULE ASSEMBLY (WORKSHOP)

As pointed out before, we did not use any drawings for the digital fabrication. Ten again, the manual assembly required not only extensive plan work but also a

physical representation of the final structure to communicate the design to the carpenter.

After checking the workshop's floor for evenness, we started to lay out the first layer of the falsework. The horizontal grid of 100 x 100 mm wood trusses was assembled right on the floor, separately for the three modules A, B and C. We assumed, that we would have to use a laser positioning system to adjust the following vertical columns of the falsework and in the cooperation with the carpenter, the craftsmen confirmed our pre-assumption, that the precision of the digital production could not be maintained in the handcraft. But the fact, that softwood is a quite flexible material, it turned out to be no problem using a slight force to position the parts. After fixing the panels to the falsework the connectors were glued in.

Nevertheless producing the parts with such precision was not wasted time, since we needed the precision for the connection slots anyhow. Before the modules left the workshop for the building site, we decided to join module A and B in the workshop.

5.2. FINAL ASSEMBLY (ON SITE)

The assembly of the 2 modules (A/B + C) on the site was equally successful. They were shipped from the workshop by a flatbed truck and fixed on he prepared steel frame structure that was equipped with a console to align the modules. Once correctly aligned, the connectors were glued in, (DIBt, 2011). The gap of the resulting joint was minimal and there was no further treatment necessary on the joint edge of the modules, other than some grinding to remove excrescent glue (Figure 7). After a week we removed the steel mounting jig, that supported the cantilever (Figure 8).

Figure 7. Left: Joint between Modules (A, B). Right: Module C. (IAM, 2012)

Figure 8. Left: Module (A, B) being moved in place. Right: Final assembly. (IAM, 2012)

6. Conclusion and Future Work

Surprisingly little adaptations had to be made during the assembly phase because of an accurate digital 3D-model from which we could benefit by simulating various scenarios. “Everything that does not work virtually, will not work physical as well”, we can state for many stage of the whole assembly process.

Timber is an animated material that can indeed be machined with a large variety of tools. Depending on the quality of timber and the complexity of the desired geometry of the processed parts, we will get highly accurate preassembled parts.

The effective operation of a digital work chain using the file-to-factory principle can be considered as successfully established in the production of complex shapes in architecture and the concept also worked in this specific research project.

For this type of wood connection we were strongly dependent on the climate conditions because of the range of the processing temperature of the glue and the humidity, which must not exceed 12% wood moisture.

Overall we can say, that the chosen method of construction is highly efficient, although it requires specific conditions on the building site, which cannot always be established. The biggest problems are the atmospheric conditions, which prevail at the building site during the construction phase. Since humidity changes the volume of wood, we were dependent on dry weather for the assembly on the building site. This is, of course, not predictable and hence requires a high degree of indoor prefabrication. On the other hand, softwood is a quite forgivable and flexible material, which allows, to a certain degree, to overcome imprecisions by pressing the parts into the right form and position.

Future work will investigate on how the workflow of the different stages of the assembly can be standardized for commercial use in building construction and how we can become more independent from atmospheric conditions.

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References

Calderon, E., Schimek, H. and Wiltsche, A.: 2011, Seeking Performative Beauty, *in* J. M. Taron, V. Parlac, B. Kolarevic and J. S. Johnson (eds.), *ACADIA 11: Integration Through Computation*, Association for Computer Aided Design in Architecture, Banff, AB, 300–307.

Deutsches Institut fuer Bautechnik (DIBt): 2011, *2K-PUR-Klebstoff PURBOND® CR 421 zum Einkleben von Stahlstäben in Holzbaustoffe*, General accredidation of building supervision, Ref.# Z-9.1-707: DIBt, Berlin.

Kieran, S. and Timberlake J.: 2004, *Refabricating Architecture: How Manufacturing Methodologies Are Poised to Transform Building Construction*, McGraw-Hill, New York.

Manahl, M., Schimek, H., Calderon, E. and Wiltsche, A.: 2012, Ornamental Discretization of Freeform Surfaces, *in* T. Fischer, K. De Biswas, J. J. Ham, R. Naka and W. Huang (eds.), *CAADRIA 2012: Beyond codes and pixels*, Chennai, India, 347–356.

Pfaller, C.: 2012, Experimentelle und theoretische Betrachtung verklebter Holz-Holz-Verbindungen am Beispiel von Freiformflächen in Brettsperrholz, MSc Thesis, TU Graz, Graz.

Scheurer, F.: 2010, The Standards of the Non-Standard, *GAM: Graz Architecture Magazine*, **6**, 180–186.

Schimek, H., Calderon, E., Wiltsche, A. and Manahl, M.: 2012, Sewing Timber Panels, *in* T. Fischer, K. De Biswas, J. J. Ham, R. Naka and W. Huang (eds.), *CAADRIA 2012: Beyond codes and pixels*, Chennai, India, 213–222.

Schimek, H., Meisel, A. and Bogenperger, T.: 2010, On connecting panels of freeform building envelopes, *CAAD – Cities – Sustainability*, ASCAAD, Fes, Morocco, 171–178.

"EPFL Learning Center, Lausanne": 2008. Available from: Design to Production <http://www.designtoproduction.ch/content/view/17/26/> (accessed 12 December 2012).

GENERATIVE AND EVOLUTIONARY DESIGN 2

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DESIGNER'S DILEMMA

The precision of numerical simulations in design systems

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Abstract. Performance based design systems are characterised through the use of performance related evaluation methods or by providing design environments which are restricting the design space according to performance criteria. The performance of a design can be evaluated by numerical simulations. With the use of numerical simulations a fundamental dilemma appears: the precision implied in numerical simulations and the imprecision of the design process itself are systematic contradictions. User control or user interaction in open systems places the user into charge of the imprecision required by the design process. In closed systems, as the below described evolutionary system, methods of imprecision have to be integrated i.e. into the precise simulation based evaluation procedure. Through tolerant selection methods and the gradual evaluation of individuals the rigid and precise system can be guided towards a design system rather than an optimisation system. Due to technical requirements which are related both to the fact of using computer systems but also to the systematic conditions implied to simulations the use of the tolerant selection methods is limited.

Keywords. Simulation based design; generative design; creativity, acoustics.

1. Introduction

With the recent spread of computer based design in the architectural domain the idea of integrating building performance as design driver into the design processes arises. The performance of a building is reflected by various criteria including but not limited to structure, function, climate or acoustics. The performance of a building can be modelled by numerical simulation. These simulations can be integrated into the design process in order to relate the design outcome to the desired performance criteria. Mainly two different ways of integration can be identified. Some approaches use simulations as an integrated and interactive solver

(Attar et al., 2009; Rippmann and Block, 2011; Ahlquist and Menges, 2011) which provides a design environment based on a set of boundary conditions in which the design evolves according to these conditions. Others use simulations as performance based evaluation tool within a generative design algorithm (Lehmkühler, 2009; Spaeth and Menges, 2011). Both approaches aim to integrate complex performance criteria early into the design process in order to implement these criteria substantially into the design outcome. Both the simulated environment in which the design process takes place and the evaluation of the design through the use of simulation takes the matter of the simulation as a major design driver into account. But the integration of a more or less scientific simulation guides the designer to a dilemma. The dilemma is based in the fundamental clash of numerical simulations and creative design processes. Numerical simulation, since they are algorithms, are characterised as to be fully determined, computable, finitely and terminated (Cormen et al., 2007). Design as a process in contrast is considered as a "wicked problem" (Rittel and Webber 1973, p. 160) or an open system. The major characteristics of this open system are the absence of a definite formulation of the problem and the lack of determination in general. (Rittel and Webber, 1973, pp. 161–167) These two premises are the poles of the dilemma of a simulation based design process. Between this span of determinism and precision on the one side and a non-determined, open-end design process on the other side a simulation based design system is located. The challenge is to integrate the precision of the expert simulation system with the generative power of the imprecise design process.

2. Integration of Performance Criteria

Within a generative design system the design goals are reflected by the definition of the evaluation criteria which are driving the selection procedure. Thus only criteria which are defined as a part of the evaluation algorithm have the capacity to contribute to and be reflected in the design outcome. Hence the evaluation procedure as a closed system doesn't provide control from outside during the process itself. This is a crucial and systematic difference to a simulation based design environment where an interactive solver is providing boundaries to the design and the evaluation is continuously carried out by an actively controlling user. Consequently in such an open system the design goals and outcomes are directly and intuitively constraint by the acting user. Thus only the performance based boundaries which the design is going to take place in have to be defined. These boundaries are limiting the opportunities of action for the user to constrain the design result to the desired performance criteria. Whereas within the closed generative system both the boundary conditions as well as the design information are to be defined beforehand. Since the design goals are under the continuous control

of the interacting user within the design environment the closed system doesn't provide any input from outside during the generative process.

Certainly the set of evaluation criteria is crucial for the success of any design system. Within the evaluation criteria both the design aspect as well as the performance aspect has to be reflected. In the discussed approach the performance aspect is represented through a numerical room acoustic simulation and the design goals which also can be considered as performance criteria are represented through morphological and functional criteria. Since all three aspects are computed by algorithmic procedures all results are rigour and precise within the given boundaries.

3. Technical Boundaries and Side Conditions

In an ideal world a design system would be an entirely open system where any imaginable criterion can be considered and any imaginable design solution could be created. Unfortunately since the design system is represented by algorithms it needs to be technically determined and limited (Cormen et al., 2007) just to make it computable.

Thus there are technical side conditions required for the design system. In the case study the creation of the geometry within the evolutionary design system is based on points in a three dimensional space. Although the position of the points is theoretically random it is necessary to limit the available domain for the points, because computers are not able to compute genuine random figures based on infinity but they need to draw the lot within specified boundaries. In consequence this means that the available space for design solution is limited by this definition. Aside the non-existence of infinity also the computable precision has to be restricted. Assuming an infinite precision would cause an infinite use of memory capacities which are practically not available. These technical restrictions apply also to the simulated environment approach where a user is interacting with the system. These computational restrictions apply to all algorithmic based design approaches but their impact to the design outcome can be reduced by providing sufficient computer power.

Aside the basic universal computational limitations also some method specific side-conditions have to be taken into account. These limitations are specific to the chosen methods within the design system and do not necessarily apply to other design systems.

The described design system is a genetic based evolutionary system. The genetic code of the individuals can be noted either as binary code or as floating point numbers. The genetic information as a binary code is demanding for a rigid definition within the structure of the genetic code. The advantage of a more easily

analysable binary code is in trade for the disadvantage of having a prescriptive domain where the solutions are located in. Within a binary description of coordinates of points i.e. the decimal has to be defined and limited in order to represent it within the binary description. This assumes that the range and precision of points is known beforehand. In many cases this is exactly what the designers don't know at the beginning of a design process. Thus this would be quite a significant restriction to the solution space where the evolutionary algorithm is searching for solutions in. The description of the individuals can also been realised by storing floating point digits in the genetic code which then limits the solution space to the capacity limitations of the computer systems only.

Within the simulation algorithm the described design system is using a combined method of a so called mirror sound source method along with a ray tracing method to analyse the acoustical quality of the enclosure. Due to the arbitrary distribution of the acoustics energy rays within the ray tracing method, the examined volume is required to be geometrically enclosed. Additionally the enclosure hull must not intersect itself. The calculation method for the acoustic quality relies also on the visibility between the sound source and the sound receiver. As soon as the sightline between the source and receiver element is blocked the acoustics calculation is incorrect. Additionally the receiver and the source must be represented as a spherical volume. As a result of these requirements all sources and all receivers not only must be included in the hull but also must have a certain distance from the surfaces.

Consequently individuals that do not include all receivers and all sound sources, or that are self-intersecting or that are not totally enclosed must be sorted out before the evaluation process is applied, because these individuals are not computable correctly by the acoustical simulation.

4. Tolerant Selection Procedures and Technical Side Conditions

The major mechanism within an evolutionary system is the selection process. In general the selection process applies not only according to the performance criteria but also according to the fulfilment of the boundary and side conditions. Individuals in the current population that don't match to the respective criteria are not selected to proceed to the next generation. Basically the threshold is a sharp borderline, where either the individual is fulfilling the requirements or not. But the strict use of the sharp borderline causes the problem of early convergence (Petzold, 1998, p. 123). The convergence problem could be solved by a tolerant selection method. The tolerant selection method enables the survival of individuals even if they do not fulfil the requirements completely. These surviving individuals can be either flagged as extraordinary survivors or they are punished with a reduction of

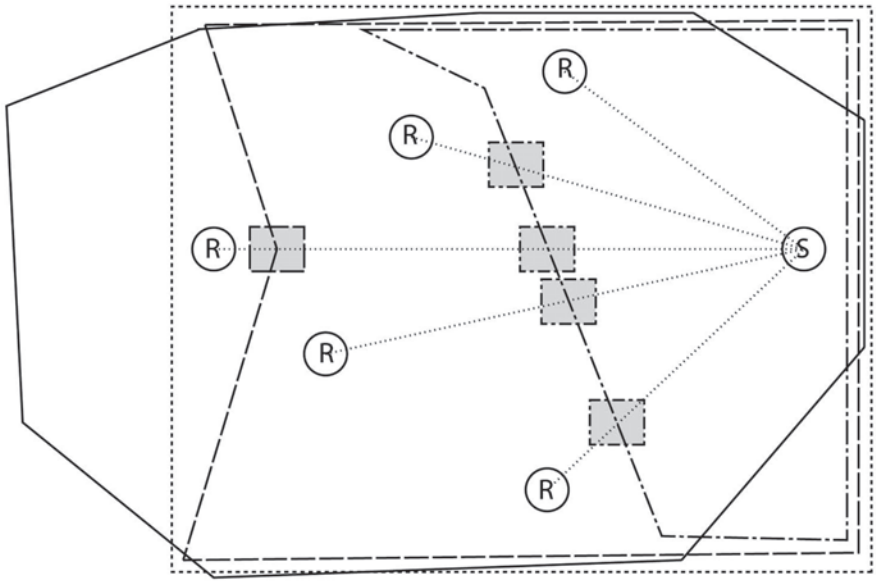

Figure 1. Diagram of the sight line prevention condition.

evaluation ratio. In Figure 1 the application and impact of a tolerant selection method is diagrammed according to the sightline prevention criteria.

In the diagram (Figure 1) the sound source is represented by a sphere (S) and the receivers are represented by another sphere (R). The dotted lines between the source and receiver are representing the sight line. With the grey hatched rectangles the violation of the side condition is marked. Given that the optimum volume is the area outlined with the dot line and three different individuals are represented through other different line types, the dashed volume is the closest to the optimum. But due to its violation of the side condition (sight line prevention) it is eliminated from the population whereas the volume represented by the continuous black line survives. If the tolerant selection method could now select not only the volume represented through the continuous line but also the volume with the dashed line into the new population the algorithm would be more efficient in finding appropriate solutions. By comparing the grade of violation through adding the distances of the violation point to the receiver a selection of minor violation could be realised.

But this method fails if the integrity of the criterion is required for the ability to compute the evaluative simulation. The basic response to this problem by avoiding computing the simulation is either the addition of a punishing value

within the evaluation process or to apply a reparation function before the evaluation process to enforce the individual to be computed. But this requires a precise knowledge of the solution domain. In order to assign a reasonable punishing value the range of evaluation values with in the population must be known. But as long as the optimum is not known, which is systematic for design processes this method doesn't apply. The reparation function might work in general but considering the special situation with the genetic description of the geometry through the notation of points and also considering the condition of non-self-intersection the establishment of a reasonable reparation function is not achievable in this context.

5. Gradual Evaluation

The acoustical simulation is delivering precise results of the sound energy based physicality in the hull. The physics based results do not represent the perceptive quality of the enclosure, but they are describing the physical reality only. Qualitative thresholds are gained through different ratios of sound energy in relation to distinguished timeframes. These thresholds are not precise values, but they are defined as more or less large ranges within specific acoustic qualities that are recognised by a majority of listeners. Asides the acoustic thresholds the rooms are also evaluated in terms of functional and morphological qualities. Through the analysis of surface distances, sizes, angles and other morphological criteria of the enclosure quality measures related to function and morphology can be gained. These quality values are also not precise digits because the functional quality of a space as a comfortable area to stay within a certain physical reality may be evaluated equally. According the tolerant selection method the quality evaluation is processed through a gradual transcription algorithm which transforms the physical simulated reality gradually into a quality measure (Figure 2).

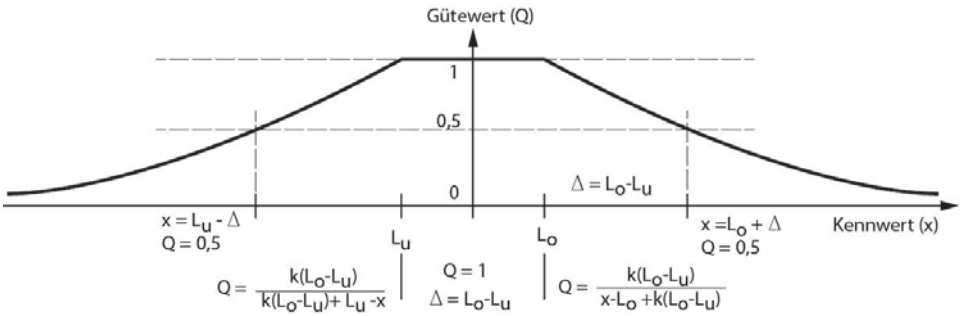

Figure 2. Transcription algorithm of physical properties into quality values.

The graph in Figure 2 shows that the gradient of the quality is in relation to the optimum area for the regarded criterion. The larger the range of this optimum area the bigger the slope of the graph is. The slope is defined through the 0.5 threshold which has the same distance on the abscissa to the lower or upper boundary value as the distance of the optimum range. Through this transformation algorithm the different ranges of optimum amongst the different criteria is balanced and related to their inherit precision.

6. Implementation of the Imprecision into the Design System

Since the proposed design system is a closed system which doesn't provide user interaction from outside the imprecision required by the nature of the design process has to be implemented into the evaluation procedure. The above exploration shows that not all of the side conditions such as sightline prevention, self-intersection or inclusion of all sources and receivers can be handled tolerantly. Regarding these strict conditions the population is created homogeneously computable by sorting out the not matching individuals and replacing them by newly created ones which are computable by the room acoustical simulation. The room acoustical simulation is carried out with the entire precision possible by the computational power. But the results of the simulation are transferred into quality measures according to the above mentioned gradual evaluation algorithm. The acoustic quality is evaluated not only by one single acoustical criterion but by various perceptive acoustic criteria and also on multiple positions in the enclosure. Alongside with this transformation other criteria such as morphological and functional criteria are integrated into the evaluation measure. The evolutionary algorithm which is searching for the design result is formulated as a maximisation algorithm which searches for the best solution using the described three main evaluation criteria, acoustics, morphology and function. Respectively the algorithm is not eliminating individuals that are failing criteria but is looking for the maximization of the quality measurement. Thus not only the gradual evaluation procedure but also the general selection method which is tolerant provides the necessary imprecision for the design system.

7. Conclusion

Although the selection of evaluation criteria is crucial for the success of the design system and although the criteria are representing design goals still they are not responding to the requirements of solving "wicked" problems. The imprecision which is required by any design process can be incorporated into a design system either by enabling user control or by integrating tolerant selection

methods and gradual evaluation procedures. Through user control the system as such can remain very precise and strict because the user is in charge to provide the imprecision for the design process. Through the gradual evaluation and tolerant selection methods the imprecision is integrated into the system itself. The extent of integrating these methods is limited by technical restrictions that are i.e. related to the applied simulation method. Thus not every criterion which is desirably treated tolerantly can be handled accordingly. And even substitutive methods like punish function or reparation function are not applicable in every case.

This exploration was done with in the development of a form finding algorithm for acoustic rooms. In the applied acoustic simulation a tolerant selection method for the sight line prevention criterion is not applicable due to the technical necessity of the receivers to be viewed directly by the source and the lack of knowing the bench marks. But for other geometric criteria, which are not included in the simulation process, like number of hull faces, or the distance of the receiver to the hull the selection of the individuals could be handled tolerantly and or gradually. Due to the lack of knowing the solution landscape punishment functions could not be applied to the evaluation procedure. But the gradual evaluation method is applied to any of the evaluation criteria.

Nevertheless the application of tolerant selection and gradual evaluation opens the closed system of evolution based generative system on the basis of an acoustic simulation towards a system that reflects the notion of imprecision in the design process and makes it act more as a design system than an optimisation system. The combination of design oriented evaluation criteria with a tolerant selection strategy keeps the potential of surprising or unforeseen results which are typical for design systems.

References

Ahlquist, S. and Menges, A.: 2011, Methodological Approach for the Integration of Material Information and Performance in the Design Computation for Tension-Active Architectural Systems, *Proceedings of the 29th Conference on Education in Computer Aided Architectural Design in Europe (eCAADe 2011)*, Ljubljana, Slovenia, 800–807.

Attar, R.' Aish, R.' Stam, J.' Brinsmead, D.' Tessier, A.' Glueck, M. and Khan, A.: 2009, Physic-Based Generative Design, *Proceedings of the 13th Conference on Computer Aided Architectural Design (CAADFutures 2009)*, Montréal, Canada, 231–244.

Cormen, T. H.' Leiseron, C. E.' Rivest, R., and Stein, C.: 2007, *Algortihmen- Eine Einführung*, 2. Auflage, Oldenbourg Wissenschaftsverlag, München.

Lehmkühler, U.: 2009, Der optimierte Entwurf und seine Berechnung: Strategien zur computergestützten Entwurfsoptimierung von Gebäuden im Rahmen der ganzheitlichen Architekturgenerierung am Beispiel von Einfamilienhäusern, Dissertation, Universität Stuttgart, Institut für öffentliche Bauten und Entwerfen.

Petzold, T.: 1998, Ein Beitrag zur Entwurfsoptimierung ebener Fachwerke mit Evolutionsstrategien, Dissertation, Universität Stuttgart:, Institut für Statik und Dynamik der Luft- und Raumfahrtkonstuktionen.

Rippmann, M. and Block, P.: 2011, New Design and Fabrication Methods for Freeform Stone Vaults Based on Ruled Surfaces, *Proceedings of the Design Modelling Symposium Berlin 2011*. Springer, Berlin, New York, 181–189.

Rittel, H. and Webber, M.: 1973, *Dilemmas in a General Theory of Planning*, *Policy Sciences* **4**, 155–169.

Spaeth, A. B. and Menges, A.: 2011, Performative design for spatial acoustics: Concept for an evolutionary design algorithm based on acoustics as design driver, *Proceedings of the 29th Conference on Education in Computer Aided Architectural Design in Europe (eCAADe 2011)*, Ljubljana, Slovenia, 461–468.

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PROTOTYPE IMPLEMENTATION OF A LOOSELY COUPLED DESIGN PERFORMANCE OPTIMISATION FRAMEWORK

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Abstract. Integration of analyses into early design phases poses several challenges. An experimental implementation of an analysis framework in conjunction with an optimization framework ties authoring and analysis tools together under one umbrella. As a prototype it served intensive use-testing in the context of the SmartGeometry 2012 workshop in Troy, NY. In this prototype the data flow uses a mix of proprietary and publicised file formats, exchanged through publicly accessible interfaces. The analysis framework brokers between the parametric authoring tool and the analysis tools. The optimization framework controls the processes between the authoring tool and parametric engine on one side and the optimization algorithm on the other. In addition to some user-implemented analyses inside the parametric design model the prototype makes energy analysis and structural analysis available. The prototype allows testing assumptions about work flow, implementation, usability and general feasibility of the pursued approach.

Keywords. Design-analysis integration; design refinement; optimization.

1. Introduction

In building design there has been increasing interest in integrating analyses into the design process at earlier stages. This poses a number of challenges like interoperability between design authoring and analysis tools, the cognitive distance between conceptual design and the detail level of information required by analysis software or actionable presentation of analysis results to designers. This research is aimed at finding solutions to these challenges. Solutions are implemented iteratively according to an agile development approach, while testing assumptions in formal and informal usability settings. This paper reports about the progress of this process, intermediate findings and conclusions for further development. The assumption is, of course, that these capabilities may enable design teams to arrive at better performing designs

when compared to traditional design approaches. This seems to be an appropriate response to today's demands for high performance buildings.

2. Challenges of Design and Analysis Integration and Pursued Solutions

Interoperability: The situation in the software industry concerned with designing buildings appears to reflect the state of the building industry at large: it is fragmented. There are many incompatible design and analysis software tools using incompatible data formats. There are various approaches towards increased interoperability: (1) A tight, closed proprietary system of software applications, unified through a proprietary data format. (2) a loose system of many software tools using as many data formats. Individual translation modules resolve data transformations as needed resulting in many one-to-one mappings. Systems like this are being proposed by some of the researchers collaborating through the Open Systems and Methods for Built Environment Modelling initiative[1] (Janssen et al., 2012). (3) A loose system of tools using an open or otherwise publicised, standardised data format like the Industry Foundation Classes (IFCs) and Green Building XML (gbXML). Latter two approaches frequently employ workflow control systems or specific structured data layers to glue the pieces together (Flager et al., 2008; Toth et al., 2012). This research project uses a mix of the first and third approaches by using a shared data representation while initially focusing on the implementation of frameworks that allow loose association of authoring and analysis tools through an application programming interface (API).

Data equivalency: Authoring tools may not allow creation of all the data required by a specific analysis tool, leading to gaps in data that prevent successful analyses. There is no general remedy to this problem. When an authoring tool does not have the capability to generate the required data there is little to do beyond alerting the designers to the problem of missing data. As a response to the challenge of data equivalency we propose an intermediary analytic framework between authoring tools and analysis tools. The analytic framework API allows analysis engines to register the type of analysis they offer as well as the data required by the analysis services.

Data discrepancy: Conceptual design moves through large ideas and concepts, and is less concerned with the detailed specification of constructions. Analysis software often requires very detailed specifications in order to compute performance of a building (Bleil de Souza, 2012). Analogous to the challenge of lacking data equivalency, missing information can be pointed out to designers based on the knowledge about which analysis services require what type of data. A complementary remedy is the search for types of analyses applicable to early design requiring only an adequate amount of information. This is a separate research project.

Speed of feedback: Design is an iterative process. Iterations are frequent and fast. Any analyses feeding back into these design iterations have to be fast enough that they remain relevant for the current iteration (Hetherington et al., 2011). In order to accelerate feedback about the design, various strategies are being pursued. In the case of this research project, opportunities in cloud computing are being investigated.

Performance proxies: As mitigating strategy to accurate but slow analyses science often uses proxy indicators which are sufficiently reliable, well enough aligned with the behaviour under investigation, and quickly computed. However, as of yet there is not sufficient research to permit use of such performance proxies.

Results display: Visualization of analysis results is not always intuitive and often not visually related to the geometry model of the design (Dondeti and Reinhart, 2011). When working with parametric design tools, there are no well-developed conventions how to compare design variants by their predicted performance (see Figures 3 and 5). Within this research project opportunities have been provided to expand investigation of results display but have not been deeply explored, yet. Initial focus in the context of design feedback has been in displaying analysis results in the context of the model.

In-context results: Analysis results are commonly only visualized in a representational way without the analysis results actually available in the digital design model for access by computational processes. Direct accessibility in the model enables automation of refinement iterations or optimisation processes. Because the goal of this research is the integration of analyses into the early design process, displaying analysis results in the context of the design is an important part of the implementation. Relevant to the idea of integration of analysis feedback into the parametric design workflow is the actual parametric accessibility of the analysis results to the computational system. In this research, analysis results can be matched with the analyzed elements so that results can be used in parametric dependencies in order to change the design as a consequence of how it performs.

Human-machine balance: Especially in early design not all design goals are measurable, commensurate, or even quantifiable at all, latter also because qualities are a strong factor in successful design. This poses the challenge how to balance computed performance metrics with qualitative aspects whose performance evaluation is based on the designers' judgments. There are several approaches possible to resolve this dilemma: (1) Avoid any type of automation and fully focus on supporting design team decisions. The design team may utilize analyses and in-context result display to inform its decisions. (2) Implement some complex, pre-defined work flow that mixes design refinement automation with interaction between the system and the design team (Geyer and Beucke, 2010).

(3) Rely on the multi-level influence the design team can exert on the entire system, from the reasoning behind the parametric model with its behaviours to the selection of parameters that are accessible by the optimization engine or the metrics for the fitness of a specific design. Additional decision support for the team may be available through an interface that allows analysis of all computed solutions, or exploration of the Pareto-optimal set of optimisation runs.

All scenarios are suited to support the design team in its tasks; however, the latter approach makes the full power of computational design available to the design team.

3. System Implementation for SmartGeometry 2012

3.1. PARAMETRIC DESIGN AND ANALYSIS WORK FLOW

High-level work flows for establishing a parametric model for design and analysis have been described in detail in various places, probably most thoroughly by CIFE (Chachere and Haymaker, 2008). The design work flow for the prototype uses a variation on the theme under acknowledgement of the difference between measurable (and computable) performance goals, and hard-to-measure (or non-computable) design goals (Figure 1).

Performance and design goals are deduced from the project goals. Performance goals determine which simulations or analyses are appropriate to help assess the

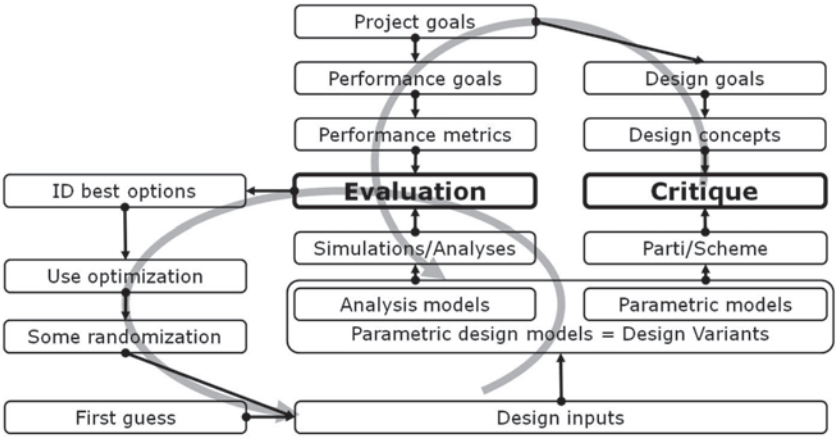

Figure 1. The parametric design and analysis workflow including human-centred critique and computation-driven evaluation and optimisation.

performance of the design. Simulations and analyses require specific analysis models. In order to generate these analysis models specific inputs are required. The set of analysis models and on the design side the design models will react to changing design inputs and generate new models as design variants, material for simulation, analysis, or the architectural design *parti*. While the results of computational simulations and analyses may be evaluated computationally, the resulting version of the design *parti* is commonly subject to human critique.

The design team may set up an automated design feedback loop that uses some optimisation scheme. The optimisation algorithm manipulates parameters that were identified by the design team in order to generate design variants for renewed evaluation. The response to the critique, or human response to any type of automated performance-driven design refinement, however, is not limited to the parametrically accessible change domain. Change could be effected at any level, starting at the top level of project goals. Deduced performance or design goals can be changed, the performance metrics, collection of simulations or analyses, or the system of parametric models can be modified, as well as the nature, range, and resolution of input variables.

3.2. PROTOTYPE FOR SMARTGEOMETRY 2012

For the SmartGeometry event in Troy, NY, in March of 2012, a first implementation step for this system was taken. The workshop cluster "Material Conflicts" used a prototype implementation of the design system (Figure 2).

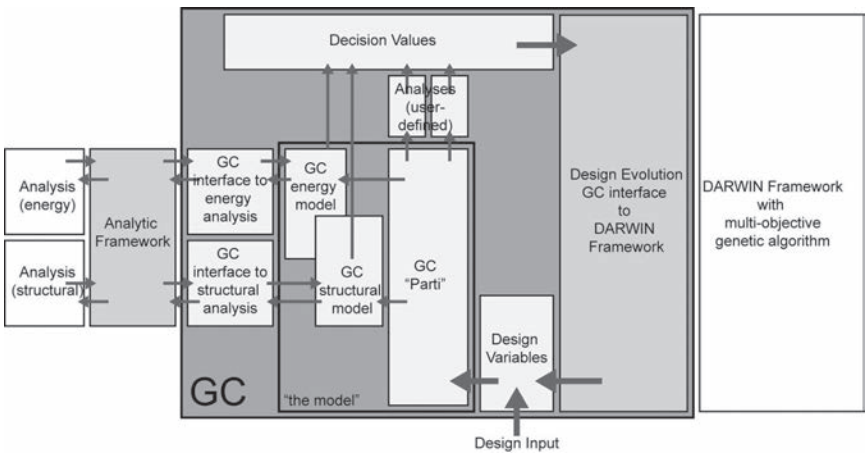

Figure 2. The architecture for the prototype at SmartGeometry 2012.

Designers create a parametric model of their design, in parts with GC features that represent structural members (nodes, beams, columns) or energetically active building elements (surfaces as walls, floors or windows). In combination with complementary project level information (project name, location, weather data, building type and foundation type) these data are routed to their respective analysis nodes in GC.

These analysis nodes communicate with the analytic framework which in turn routes the analysis requests with all required data to the analysis engines. In the prototypical implementation, analysis engines reside either on the client computer or in "the cloud", in this case Microsoft Azure. Post-processing scripts extract a selection of analysis results. The analysis framework transmits these analysis results back to the analysis nodes in GenerativeComponents where they are made available for further computational consumption for example to determine a design's fitness in form of decision values.

The decision values are passed to the Design Evolution node in GC, which connects to the Darwin Framework and its evolutionary optimisation algorithms.[2] Designers also identify all design variables that they want to be considered changeable for design iterations, indicating what the design's genome is that the evolutionary algorithm needs to consider. After evaluating the genome, the optimisation framework generates genotypes for all individuals in a generation's population and then waits for all fitness values to arrive. It evaluates the fitness of the individuals to determine the next parent genome and develop the next generation's phenotypes.

3.3. LIMITATIONS OF THE IMPLEMENTATION

Prototype implementation will always remain limited and some of those limitations are prone to overshadow other observations. Analysis models were kept at the minimal implementation necessary to allow analyses to execute while possibly achieving sufficient completeness of the models for conceptual design. The prototype suffered from a general lack of robustness and the variables that could be optimised were limited.

3.4. USER EXPLORATIONS AT SMARTGEOMETRY 2012

Material Conflicts cluster participants explored various approaches with the prototype system. Optimisation schemes that were examined comprised an urban study for Penang by Greig Paterson of Aedas (Figure 3), a natural ventilation scheme utilizing a modulated stack effect by Lem3a and Kristoffer Negendahl (Figure 4), and Dr. Woodbury's exploration of an alternative representation of a Pareto front (Figure 5).

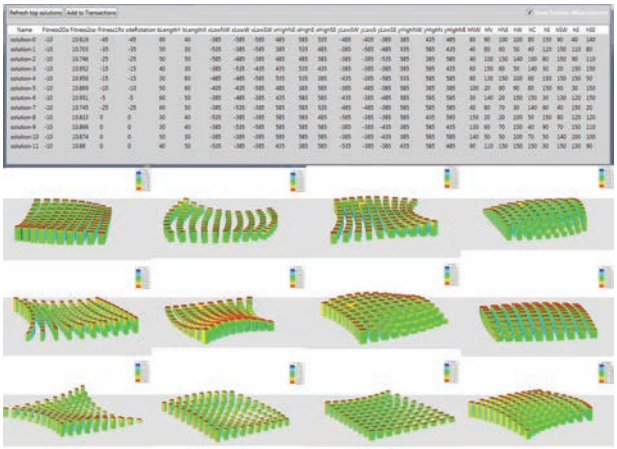

Figure 3. Greig Paterson's urban scheme for Penang - twelve top solutions.

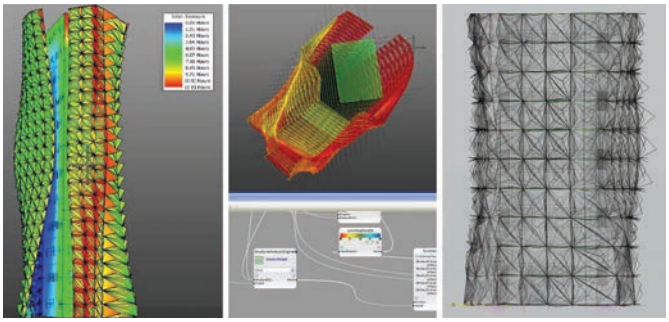

Figure 4. Lem3a's and Kristoffer Negendahl's stack effect utilization for natural ventilation, optimization of envelope to modulate stack effect in relation to window openings.

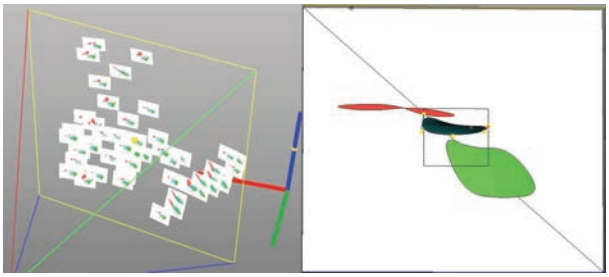

Figure 5. Dr. Woodbury's experiment in Pareto-front visualisation.

3.5. CONCLUSIONS FROM SMARTGEOMETRY EXPERIMENTS

There were various lessons learned, suspicions or prior awareness confirmed, and assumptions refuted during the experiments at SmartGeometry 2012:

- Special features representing elements for analyses cannot be added to the parametric platform in a sustainably scalable manner. With additional analyses the solution must pursue flexible utilization of existing features rather than the addition of more specialized features.
- Some assumptions made for simplification of user input of required analysis data were shown to be too limiting.
- Some features such as shading surfaces in the energy model or explicit tagging of foundation nodes in the structural model had been omitted due to time constraints; however, the user explorations at Smartgeometry 2012 confirmed that they are necessary features for conceptual design.
- The analytic framework needs to include on the parametric platform side an automatically generated footprint based on the specifications of required inputs by the analysis engine that registers with the analytic framework. It is not a sustainable solution to add analysis nodes for each new analysis type.
- Analysis failures did not post clear messages about reasons of failure to the users. Most failures occurred due to errors in the data submitted to the analyses. A validity check for analysis data appears like a helpful addition. Certainly improved error reporting would already increase usability.
- Some work flows pursued by workshop participants clearly lead to models that required additional clean-up before submitting them to analyses. However, these work flows appear common enough to pose a constant challenge to such analysis-intensive design approaches.
- Running only the analyses in the cloud adds a triple penalty of sending the request with the required data to the cloud, slower processing on usually low-performing cloud nodes and extraction and download of analysis results from the cloud to the parametric platform for further processing.
- The average wait time of a job on the cloud was 6 seconds which with appropriate parallelization of analyses with longer durations appears feasible in light of the expected overall time savings.
- Individual analyses took anything from fractions of seconds to several minutes to several hours, latter case certainly an outlier; however, if an analysis like that were executed for an individual in a population generated by an evolutionary algorithm it would delay progress on that generation. There may be other approaches necessary for the optimisation framework to deal with such outliers without delaying the overall progress of the optimisation. Without this outlier, average analysis job duration was 1’46”.
- The optimisation framework’s interface was lacking robustness; it was not possible to assess the optimisation framework’s performance because of that. However, some optimisation runs did execute for a fair amount of generations indicating the potential of this technology.

4. Ongoing and Future Work

Based on the results of the experiments at SmartGeometry 2012 and subsequent experiments work has focused in several areas:

- Increasing the robustness of the analytic framework.
- Increasing the robustness of communications between software components and services on the cloud.
- Refactoring of the optimization framework for robustness.
- Redesigning the user interface to the optimization node in the parametric model.
- Increasing the "completeness" of the analysis and simulation models without increasing required model complexity.
- Increasing the capabilities of the analytical models, for example by adding automated zone creation for energy analysis.
- Redesigning the software architecture so that all components can run as services on the cloud in order to minimize cloud upload and download penalties while at the same time maximizing parallelization in the cloud (Figure 6).
- Find proxy analyses or simulations that may guide conceptual design with sufficient reliability while executing at speeds superior to traditional analyses.

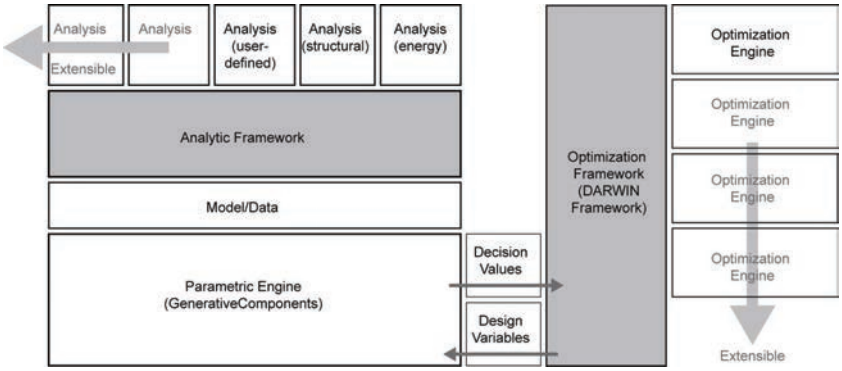

Figure 6. Conceptual sketch of cloud services architecture.

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Endnotes

1. Open Systems and Methods for Built Environment Modelling initiative. Available from: <http://www.linkedin.com/groups?home=&gid=4000091&trk=anet_ug_hm> (accessed 7 December 2012).
2. Darwin Optimization (version 0.91) by Dr. Zheng Yi Wu. Available from: Be | Communities <http://communities.bentley.com/communities/other_communities/bentley_applied_research/w/bentley_applied_research__wiki/6584.aspx> (accessed 7 December 2012).

References

Bleil de Souza, C.: 2012, Contrasting paradigms of design thinking: The building thermal simulation tool user vs. the building designer, *Automation in Construction*, **22**, 112–122.

Chachere, J. and Haymaker, J.: 2008, Framework for Measuring Rationale Clarity of AEC Design Decisions, *CIFE Technical Report TR177*, Stanford University.

Dondeti, K. and Reinhart, C.F.: 2011, A "Picasa" for BPS – An interactive data organization and visualization system for building performance simulations, *in* V. Soebarto and T. Williamson (eds.), *Proceedings of Building Simulation 2011: 12th Conference of International Building Simulation Association*, Sydney, Australia.

Flager, F., Soremekun, G., Welle, B., Haymaker, J. and Bansal, P.: 2008, Multidisciplinary process integration and design optimization of a classroom building, *CIFE Technical Report TR175*, Stanford University.

Geyer, P. and Beucke, K.: 2010, An integrative approach for using multidisciplinary design optimization in AEC, *in* W. Tizani (ed.), *Proceedings of the International Conference on Computing in Civil and Building Engineering*, Nottingham University Press.

Hetherington, R., Laney, R., Peake, S. and Oldham, D.: 2011, Integrated building design, information and simulation modelling: the need for a new hierarchy, *Proceedings of Building Simulation 2011*, Sydney.

Janssen, P., Stouffs, R., Chaszar, A., Boeykens, S. and Toth, B.: 2012, Data transformations in custom digital workflows: Property graphs as a data model for user-defined mappings, *International Workshop: Intelligent Computing in Engineering 2012 – EG-ICE 2012*, Munich, Germany.

Toth, B., Boeykens, S., Chaszar, A., Janssen, P. and Stouffs, R.: 2012, Custom digital workflows: A new framework for design analysis integration, *in* T. Fischer, K. De Biswas, J. J. Ham, R. Naka and W. X. Huang (eds.), *Beyond Codes and Pixels: Proceedings of the 17th International Conference on Computer-Aided Architectural Design Research in Asia*, Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, 163–172.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 685–694. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

RESEARCH IN PRACTICE

An exercise in generative urban massing

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Abstract. The following paper explores practice based research as a means of identifying issues within current urban design methods. It considers the application of parametric systems as a means of addressing these issues. These systems are developed and tested across both Australian and international urban design projects within Grimshaw Architects. A methodology is proposed for the development and application of these parametric tools across multiple scales of design resolution. It reports on the application of a set of parametric urban scale massing tools in real world design projects. This exploration is carried out in distinct phases of design defined by the scale of resolution. The phasing allows for discrete problems to be addressed more effectively at different stages of the design process while still encouraging a seamless, bi directional workflow through a digital master model.

Keywords. Computational design methodology; parametric design; city modelling.

1. Introduction

Computational Design Methodologies play a variety of roles in the analysis, design and construction of buildings. Computational and parametric design methods are no longer foreign to the processes of design in practice. In particular, recent developments in parametric design have allowed for a greater expression of complex ideas and design. These programs have defined a new methodology in practice and research in the field of non-standard architecture (Stavric and Marina, 2011). Despite

this growing trend, design outcomes continue to suffer from serialisation, standardisation and a proclivity towards geometric primacy (Vincent et al., 2010). This highlights the need to reassess how we employ emergent technologies in architectural practice and whether it can be seamlessly integrated into existing design methods.

For example, there is rapidly growing research in the application of parametric systems to the complexities of urban design. Unfortunately very little of this research has been resolved in terms of a tested and replicable design methodology that quantifies cause and effect of parametric application within our current design practice (Schnabel and Karakiewicz, 2007; Tang and Anderson, 2011). The 'black box' of technological toolkits are unattainable for the majority of design practitioners. Technologies and, contemporary problems in design practice need to be coupled through "embedded research" in practice (Maher et al., 2006).

This paper explores embedded research as a mutually beneficial knowledge sharing exercise that aims to bridge the gap between the worlds of academic research and architectural practice. It reports on the development and application of a set of parametric urban scale massing tools across a series of real world design projects. This exploration is carried out in a series of distinct phases which have been defined by the scale of design resolution. The process demonstrated in the following case studies adhere to a set of general rules for parametrically generated urban design.

- Models are limited to indicative massing diagrams in both 2 and 3 dimensions.
- Information has to be universally understood between the required digital systems as well as the human stakeholders and designers at any point in the process. This limits data loss and misinterpretation as well as reworking of digital data for human consumption.
- Any system has to be capable of both scaled intervention and scale less automation. Although bi directional parametric models can be considered scale less, the human process of design and problem solving still requires the defragmentation of scale and complexity.

2. Benefits of Parametric City Modelling

The inadequacy of traditional urban design and planning techniques and standards is widely recognised as insufficient for creating successful urban developments (Lowry, 1965; Ingersoll, 2006; Cuthbert, 2007). The potential for unifying current technological capabilities and the practice methods of urban designers is one way to address this problem. Parametrically governed systems have the capacity to compute large sets of complex data and generate outcomes from pre-defined inputs and control parameters. This sets up a recognised problem in urban design complexity with an accessible system that has the potential to address the shortfalls in traditional design approaches. This complexity and multiplicity of scale can benefit from a set

of programming and visualisation interfaces designed to manage large data sets and optimise physical forms as determined by the designer (Stavric and Marina, 2011).

The case studies presented in this paper explore these interface issues through the following research questions. Firstly, how can urban design aims and requirements (parameters) be communicated successfully for use and utilisation in parametric programs? Secondly, how can this language be reduced in complexity to be used as a problem-solving medium while still retaining an inherent and explicit understanding of the embedded complexities?

3. Massing and Density Modelling as a Method of Diagramming

Massing refers to the built mass that occupies a site and is crucial in defining typology, scale and grain of a site. Density and distribution affect the spread of mass across a given area which in turn creates a certain ratio of built to open space. These areas are of particular interest in parametric city-scale modelling as a means of defining design intentions in the early stages of the design process and structuring desired typological patterns and relationships. Massing and density modelling is used here as a means of diagramming 3D concepts. This limitation of scope to massing diagrams defines the first rule of the proposed parametric method.

Urban models need to cover multiple scales of consideration and critique during design. New insertions therefore, need to be similarly linked into existing networks in order to be successful and survive. The case studies have been formed on the basis that these levels of design can be classified under four scales of consideration: Region, Community, Block and Building (Galiana, 2010).

Traditionally, this scale-based design method is approached as a linear series of snapshots. Decisions can only be made at one point or scale and then manually updated and validated sequentially at each of the other three levels. A parametric approach can set routine assumptions and prevailing conditions as constraints. In effect this creates a single working scale, zooming sequentially in or out in scale of resolution. This framework allows for a single digital working model to be formed and tested at any scale as the design develops. As a result, instead of the scale or working medium dictating process, the appropriate workflow of design thinking, as determined by the designer, defines the design across all scales continuously (Figure 1).

An important distinction to make with this definition is between the scale of design resolution and physical scale. The four scales of design fall under the category of physical scale which is a literal translation, represented by ratios relative to real life (1:1). Design scale is more fluid, and although it generally adheres to the rules of physical scale it is more concerned with resolution of ideas and consideration in the design process. This distinction is relevant to the diagrams in

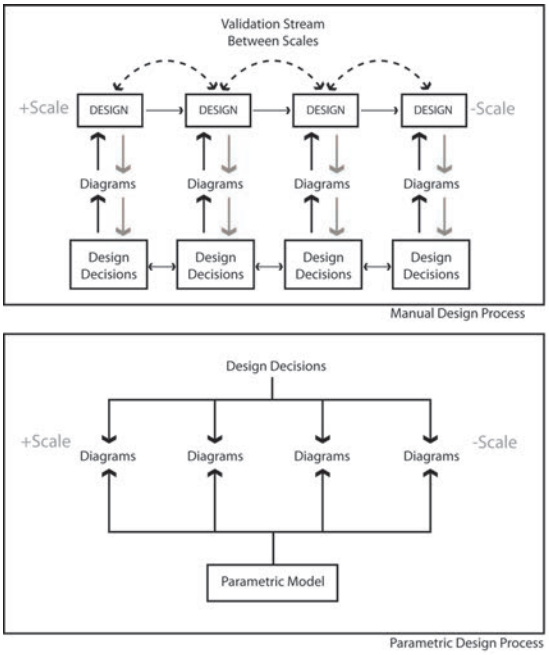

Figure 1. The manual and the parametric design chains.

Figure 1, because although parametric modeling has the ability to address all physical scales simultaneously, there is still a process of refining the scale of design thinking. This is still beneficial to the process as a design has only one shifting scale of linear consideration while the other is automated. Traditional methods require management of these two shifting streams, with design changes checked linearly back and forwards against each. This over complexity requires careful management of all current designs across all physical scale to ensure all are telling the same story and forming a singular, cohesive design.

4. Parametric Urban Design Methodologies

The following methods have been developed and tested across a number of urban scale studies and master planning exercises as well as a mix of both residential and commercial multi-storey building feasibility studies. The parametric generation reduces a large portion of the manual modelling processes as well as the measurements and calculation area schedules. This opens up the design process for more thorough testing of potential masterplan options as well as allowing for higher level feasibility testing on performance analysis, code compliance and

impact analysis. Each of these scales is presented individually to highlight the unique problems that arise in each. The end result is a single design modelling process that builds levels of detail as each finer grain is considered. The process of creating this master model is linear in terms of its macro to micro design process. Despite this, at any point in this timeline, the model can be considered as bi directional in its ability to simultaneously consider all data previously collated.

4.1. REGION

Regional scale design methods focus on analysis of existing site conditions and context as well as initial mapping out of design aspirations that will govern the subsequent finer grain decisions. Most of the problems that occur at this level of design are to do with the analysis of large, complex sets of conditions and constraints that will affect the design scheme. Whether the design is Greenfield or Urban Infill, the main aim of this phase of design is to gain an understanding of current state of play and begin to test the tolerances and opportunities for any new design addition.

Recent advancements in urban databases and Geographic Information Systems (GIS) have allowed for even more contextual information to be accessed than purely manual or visual assessments. The result of these collections of information is often too great to analyse manually but lends itself well to automated parametric analysis that can target and test specific data and return results that are relevant to a particular design. The design tools that have been developed and tested are classified under the headings, Existing Conditions Analysis and Design Intervention Tools (Figure 2).

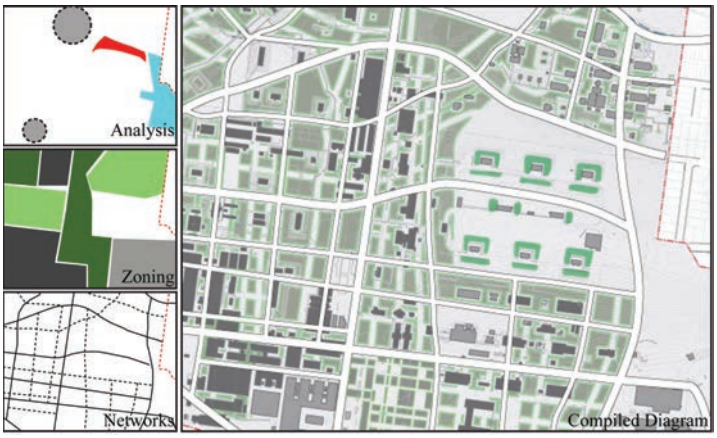

Figure 2. Levels of regional design control and a resulting plan diagram for use as a parametric input.

The site analysis tools aim to return information about existing buildings and their relative importance, key nodes of activity, prevailing environmental conditions, infrastructure, servicing and geological data. Each of the tools that have been developed has aimed at returning the raw and often numerical data to the designer in a form that is more easily understood, manipulated, and communicated.

The key to the success of these tools has been to develop a simple language of diagramming the existing conditions analysis along with new design ideas from physical to digital mediums. From this format, the information can then be managed in a single parametrically governed model. The design studies have utilised a relatively simple form of substitution to inform the model with both perceivable and imperceptible data. Colour is used as a perceivable means of communication, defining different changes in the model such as key nodes, zone types or networks. As a means of communication, definitions by colour are the easiest form of communicating to human participants as well as having the ability to be understood numerically or digitally. The imperceptible information can take different forms, but is most readily understood as layers or object classifications. This type of data classification is imbedded in the live diagram and controls aspects of the design that does not need to be visually communicated or allow a base classification of design parts when the perceivable outputs are variable.

4.2. COMMUNITY

The community scale design tool is a means of applying indicative sites within the previously defined design zones. These general massing envelopes are governed by regional governance, building type compositions within zones and any of the relevant Existing Conditions Analysis as well as adding mass to form a full 3D design diagram (Figure 3).

Division and subsequent massing are controlled by variable parametric algorithms controls by community scale precedent benchmarking.

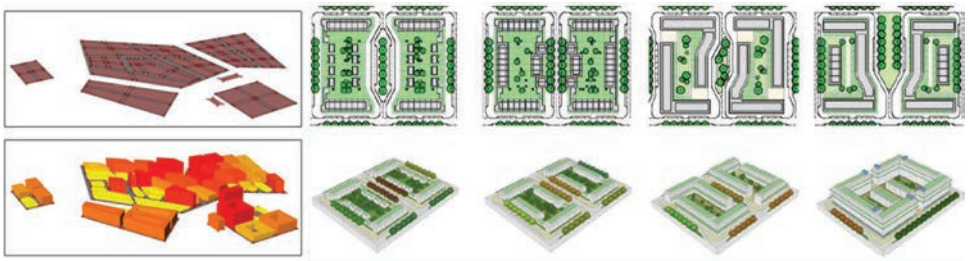

Figure 3. Community zone division and massing envelopes.

The basic zone forms are taken from the regional scale design diagrams. These regions are analysed for type and size and divided into basic block and building scale parcels. This stage sets the basic envelope footprint and height constraints for later stages and tests the overall site composition and capacity against contextual information, planning governance as well as visual impact and design analysis.

4.3. BLOCK

The block scale design application adds standardised building types into the envelope constraints defined in the community studies. This level of application relies heavily on external benchmarking information in order to test the potential success of different design aspirations.

This type of block composition studies can often be conducted in isolation from the parametric process. Type and typologies can be benchmarked and catalogued in order to test new schemes quickly. From this type of study, design aspirations for a new scheme can be quantified as general building data that can inform zone arrangement and the composition of the blocks they contain (Table 1).

The modelling process for this is very similar to that of the previous community scale massing phase. The main points of difference are in the benchmark or case study derived input information and the ability for the parametric tools to generate varying type clusters based on variable control inputs.

Table 1. Example breakdown of building types and distribution as determined from benchmarking studies (Figures Courtesy of Grimshaw).

	Mix	**Beds**	**Sq ft**	**Sq m**	**Parking**
Detached	5%	3	1050–1250	98–116	2
	5%	4 to 5	1250–1600	116–149	2
Semi Detached	15%	3	925–1050	85–98	1(50%) to 2(50%)
	20%	4	1150	106	2
Terrace	15%	2	750–900	69–83	1
	20%	3	950	87	1(50%) to 2(50%)
Flats	10%	1	500–550	46–51	0.7
	10%	2	650–700	60–64	0.7

4.4. BUILDING

The purpose of this level of modelling is to more accurately address aspects of building design requirements within the constructs already set during design

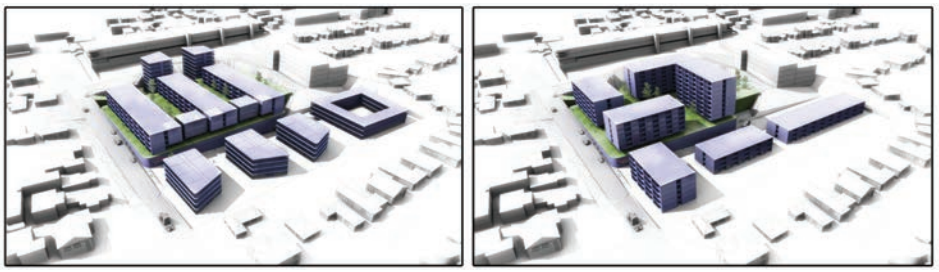

Figure 4. Examples of Parametrically Defined Building Options. (Image Courtesy of Grimshaw).

development. In some aspects this scale has proved most difficult in the development of parametric design tools. This scale of design is often too great to apply across an entire master-planned design but has proven useful for testing key areas in a site.

The results of these snapshot studies can then be generalised to further inform the block level design inputs. The following methods were, therefore, developed over a number of smaller scale feasibility studies and were aimed at very quickly testing built mass, site capacity and yield as well as visual impact of any new development. The model, demonstrated in Figure 4, was an optioneering exercise that was aimed at testing the potential Net Lettable Area (NLA) yield of a given urban zone and the resulting impact on the surrounding context.

As opposed to other scales of design, this phase was more closely linked into the excel file as a means of both outputting and inputting information. The results of this level of massing information were much more sensitive so the model required a means of directly changing yields to meet lettable goals. In the demonstrated case, subsequent changes to yield were seen in the relative heights of the building mass but could just as easily be programmed to expand floor plates outside the predefined block restraints through horizontal controls (Figure 4). Through a set of pre defined type constraints, the model could either report back or be controlled by building mass to open space ratios for the site, heights, building separations, light access, plant and core requirements, circulation as well as unit numbers, sizes and/or commercial NLA. It is the intent to avoid any building specific architectural design response and make the output imagery clearly typological and demonstrative. A minimum of building information is generated by this set of parametric tools.

5. Conclusions

This paper describes a method for addressing practice based urban design through the utilisation of digital and parametric mediums in the design process. This

method utilises simple diagramming formats with imbedded information that is readable by designers and stakeholders as well as the computer analysis and generation tools proposed. This approach allows designers to streamline workflows by eliminating the need to convert, redraw, or alter design information in order to communicate between human and digital formats.

Benefits of the parametric design process have been in the single live model that has the ability to interpret input data and output readable formats for further work across all four scales of consideration. This process is aimed at minimising data loss and misinterpretation through the import, export and communication of a design. The design method proposed still follows traditional practices of design thinking in macro to micro processes. Unlike traditional linear methods of design, at any point in the design timeline, the process is bi directional and self critiquing.

Some of the benefits of the embedded research process have been the identification of relevant design problems that affect practice as well as having constant checks and validation of design methods. This has led to a better understanding of the methodology, parametric tools and the resulting design outcomes. One of the disadvantages to this process has been the time constraints placed on live practice projects and the misalignment between client driven workflows and the required research and development of new parametric systems. This process requires multiple projects of a similar type to allow for development outside of a specific projects timeline while still enabling retesting against other new case study design problems as they arise.

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References

Cuthbert, A.: 2007, Urban Design: requiem for an era - review and critique of the last 50 years, *Urban Design International*, **12**(4), 177–223.

Ingersoll, R.: 2006, *Sprawltown: Looking for the City on Its Edges*, Princeton Architectural Press, New York, NY.

Lowry, I.: 1965, A Short Course in Model Design, *Journal of the American Planning Association*, **31**(2), 158–166.

Maher, M., Nelson, A. and Burry, M.: 2006, Embedding research within the context of architectural practice, *Working Papers in Art and Design* **4**. Available from: <http://sitem.herts.ac.uk/artdes_research/papers/wpades/vol4/amafull.html> (accessed 4 March 2013).

Schnabel, M. and Karakiewicz, J.: 2007, Rethinking Parameters in Urban Design, *International Journal of Architectural Computing (IJAC)*, **5**(1), 84–98.

Stavric, M. and Marina, O.: 2011, Parametric Modelling for Advanced Architecture, *International Journal of Applied Mathematics and Informatics*, **5**(1), 9–16.

Tachieva, G.: 2010, *Sprawl Repair Manual*, Island Press, Washington, DC.

Tang, M. and Anderson, J.: 2011, Information Urbanism: Parametric Urbanism in Junction with GIS Data Processing and Fabrication, *ARCC 2011 – Considering Research: Reflecting upon current themes in Architectural Research*, Detroit, MI, 661–668.
Vincent, C., Nardelli, E. and Nardin, L.: 2010, *Paramertics in Mass Customisation, SIGRADI Conference Proceedings*, Bogota, Colombia.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 695–704. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

EXPLORATION OF URBAN STREET PATTERNS

Multi-criteria evolutionary optimisation using axial line analysis

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Abstract. In urban design, researchers have developed techniques to automate both the generation and evaluation of urban street patterns. In most cases, these approaches are investigated in isolation from one another. Recently, a number of researchers have attempted to couple these approaches, in order to enable larger numbers of street patterns to be generated and evaluated in an iterative loop. However, to date, the possibility of fully automating the generative-evaluative loop using optimisation algorithms has not been explored. This research proposes an explorative design method in which urban street patterns can be optimised for multiple conflicting performance criteria. The optimisation process uses evolutionary algorithms to evolve populations of design variants by iteratively applying three key procedures: development, evaluation, and feedback. For development, a generative technique is proposed for constructing street patterns. For evaluation, various performance measures are used, including in particular Space Syntax based Axial Line analysis. For feedback, a Pareto-ranking algorithm is used that ranks street patterns according to multiple criteria. The proposed method is demonstrated using an abstract scenario in which orthogonal street patterns are evolved for a small urban area.

Keywords. Axial line analysis; generative modelling; evolutionary algorithms; decision chain encoding; urban street patterns.

1. Introduction

The idea of automating certain parts of the urban design process has been around since 1960s. Since then, researchers have developed a wide variety of techniques to automate both the generation and evaluation of urban design. This research will focus in particular on the generation and evaluation of street patterns.

For generating street patterns, researchers have investigated a number of generative techniques. Duarte et al. (2006) described the generative modelling of the

Medina of Marrakech by combining a top-down and bottom-up hybrid models. Braach and Fritz (2010) used Voronoi partitioning in the generative modelling of street patterns. Both Parish and Muller (2009) and Chen et al. (2008) generated urban street patterns using Lidenmayer systems (L-systems).

For evaluating street patterns, researchers in the field of Space Syntax have since the 1970s been developing and refining various tools and theories (Hillier and Hanson, 1984; Hillier, 1996; Hanson 1998). Space Syntax methods translate overlapping convex spaces into a series of graph structures that can be analysed and interpreted in terms of their two-dimensional spatial characteristics. One of the key methods is the *Axial Line* method, which creates such a graph by generating a set of overlapping sight lines, referred to as *Axial Lines*.

For Axial Line methods, the main concepts are that of *depth* and *integration*. Depth described the minimum number of Axial Lines that need to be traversed in order to get from one space to another space. Integration describes the minimum depth between one space and all other spaces. Integration can also be calculated for a certain radius *n*, in which case it measures the total number of spaces that can be reached from a particular space by traversing *n* Axial Lines. Integration at a low radius (for example n = 3) is referred to a *local integration*, while integration without specifying any radius is referred to as a *global integration*.

Depth and integration are measures associated with particular spaces within a spatial configuration. However, these measures can also be used as a basis for calculating some more general measures that describe characteristic of the overall spatial configuration. Two such measures are the *mean depth* and the *R^2 correlation*. The mean depth measures the mean of all the depths from every space to every other space in the spatial configuration. A low mean depth may be desirable, as it is seen to represent better integrated spatial configurations. The R^2 correlation is slightly more complex. To calculate R^2, both local and global integration values are calculated for every space in the spatial configuration, and a scatter plot is generated of local versus global integration. The R^2 correlation is then calculated as the statistical correlation between these two sets of values, also referred to as the *coefficient of determination*. A high R^2 correlation may be desirable, as it is seen to represent the intelligibility of the spatial configuration (Hillier, 2002).

Research using Axial Line methods focuses mostly on the analysis of existing street patterns rather than the synthesis of new street patterns. A number of researchers have been exploring how these techniques can be used as a way of evaluating alternative urban design proposals. Hillier et al. (2008) used Axial Line analysis to evaluate design proposals in the Jeddah Urban Regeneration Master plan. Existing urban fabric and the old local plan were examined in order to observe the connectedness of neighbouring towns to the historic core. The proposed design option was then simulated to predict its effectiveness. Stonor (2009)

showed similar evaluation of the design proposal for Trafalgar Square, London. Both cases used Axial Line analysis in an "analyse, observe, predict" framework.

Recently, a number of researchers have combined generative urban modelling and Axial Line analysis in an iterative manner, where each iteration is applied manually. For example, Al-Sayed (2012) used Axial Line analysis to evaluate different iterations for hypothetical urban street patterns. Generative modelling techniques were used to create a variety of street patterns, which were subsequently evaluated for their R^2 correlation. Certain street patterns were then selected and further analysed. In another experiment, Canuto (2012) created different iterations of an abstracted urban grid followed by evaluation using Axial Line measures, as well as a set of other measures known as *urbanity ratios*. Both experiments showed the possibility of iteratively combining the generation and evaluation of urban street patterns to optimise a number of design variants.

Despite significant research in the areas of urban street pattern generation and evaluation, no research has explored the automated optimisation of street patterns using optimisation algorithms. This paper proposes such a method for the automated evolution of street patterns. The proposed method is demonstrated using an abstract scenario in which orthogonal street patterns are evolved for a small urban area.

2. Demonstration

The proposed method combines three techniques: the generative modelling of street patterns (generation), Axial Line analysis of street patterns (evaluation), and optimisation of street patterns using Evolutionary Algorithms.

Evolutionary design (Frazer, 1995; Bentley, 1999; Caldas, 2001; Bentley, and Corne, 2002; Janssen, 2004) is an approach that evolves populations of design variants through the iterative application of a set of computational procedures. The developmental procedure generates design variants, one or more evaluation procedures assess the performance of design variants, and the feedback procedure drives the evolutionary process by applying selective pressure to the population.

The use of Evolutionary Algorithms allow large numbers of alternative design variants to be considered in a fully automated way, thereby allowing optimised street patterns to be generated. The Evolutionary Algorithms here act as a way of "closing the loop" between generative modelling of street patterns and Axial Line analysis of street patterns.

The evolutionary process is executed using Dexen, a distributed execution environment for population based algorithms (Janssen et al., 2011). This system is coupled to a procedural modelling environment called SideFX Houdini, which is used for creating both the developmental and evaluation procedures (Janssen and Chen, 2011). The feedback procedure is generated automatically by Dexen, and

uses a Pareto-ranking algorithm that ranks street patterns according to multiple criteria. The results of the evolutionary process are plotted as a scatter plot using a data analytics package called Tableau.

2.1. DEVELOPMENTAL PROCEDURE

For the developmental procedure, a generative technique called *decision chain encoding* is used to generate street patterns (Janssen and Kaushik, 2013). The decision chain encoding technique structures the street pattern generation process as a sequential chain of decision points, where each decision consists of a 'design move' that inserts an urban block into the urban grid. Each time a block needs to be inserted, a gene will be used to select a move from a list of possible valid moves.

The starting condition for the developmental procedure consists of a library of urban blocks together with an empty urban area with a boundary condition at the periphery. The task is then to fill the empty urban area with some combination of blocks from the urban block library. The way that the blocks are inserted and orientated results in a variety of urban streets and squares with varying spatial qualities. Figure 1 shows the starting condition on the left and six steps in the decision chain process on the right.

The decision chain process continues to add blocks until either no more blocks can be inserted or until a certain maximum is reached. In this case, the maximum

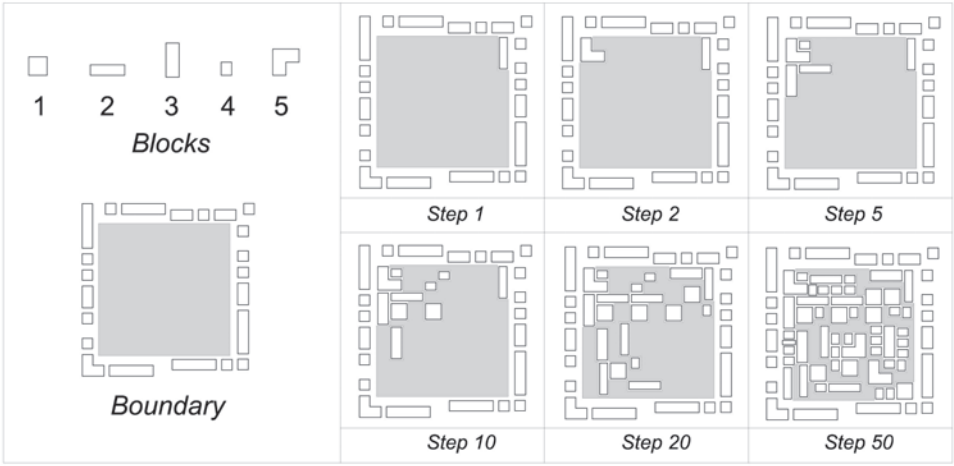

Figure 1. Sequence of generative street modelling.

was set to be 100 blocks (which was in fact never reached). Since 100 blocks require 100 decision points, the genotype is also set to be 100 genes long. Genes are real values in the range {0, 1}, which are used to select valid moves by mapping to an integer range {1, *n*}, where n is the number of valid moves for that particular decision point.

2.2. EVALUATION PROCEDURES

Three separate evaluation procedures are defined which are used to evaluate each street pattern. The three procedures are used to calculate three performance criteria: the *R^2 correlation*, the *average line length*, and the *total footprint*. The R^2 correlation has already been described above and in this case measures the correlation between local integration with a radius of 3 and global integration. The average line length measures the average length of all Axial Lines. Lastly, the total building footprint measures the total footprint of all urban blocks.

The R^2 correlation is seen as measuring intelligibility, and therefore the optimisation system is set to maximise this performance criteria. One way of achieving this is by generating a regular urban grid with long straight streets. For such a grid, the average line length will therefore be very high. However, research by Hillier (2002) has suggested that historical urban street patterns typically have a few long Axial Lines combined with many short Axial Lines. For the optimisation algorithm, we therefore set the average line length to be minimised. The first two performance criteria are therefore defined to be in conflict with one another, as street patterns cannot have both a high R^2 correlation and a low average line length. Such a conflict is seen as being desirable, as it is likely to result in a range of performance trade-offs. Lastly, in order to encourage the optimisation system to generate high density street patterns, the third performance criteria is added for the maximisation of building footprint.

This research is not suggesting that the selected performance criteria are sufficient as a basis for evaluating the quality of a particular street pattern. Performance criteria will vary on a case-by-case basis and may include a wide range of factors. Rather than being used as a tool for global optimisation, this research imagines such tools to be used in a more exploratory mode. The solutions that are evolved should therefore not be seen as being the best answers, but instead as a provocation for deeper analysis and exploration.

In order to calculate the R^2 correlation and the average line length, Axial Lines need to be generated and analysed. A Space Syntax software tool exists that can be used for this, called Depthmap. However, the tool cannot be easily automated by another program and as a result it was not used in this case. Instead, a custom plugin was created for Houdini. Within Houdini, two separate algorithms were

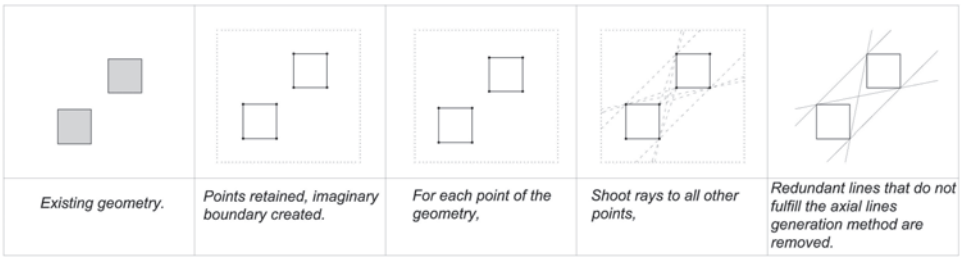

Figure 2. Axial Line generation in Houdini.

implemented: one for generating the Axial Lines, and another for analysing the Axial Lines. The Axial Line generation algorithm is implemented using built-in ray functions within Houdini following the method described in the Space Syntax literature (Turner et al., 2004; Ostwald, 2011). The Axial Line analysis algorithm first translates the Axial Lines into a graph representation and then calculates integration values. The graph calculations are performed using a general-purpose graph library called NetworkX.

In order to validate the results, a number of tests were carried out, comparing the generation and analysis of Axial Lines in Houdini to the results obtained from Depthmap. Although the Houdini technique was found to generate slightly fewer Axial Lines than Depthmap, there was only a 1.4% difference in *mean depth* and 0.2–5% difference in *integration values*.

Houdini was therefore used to define all three evaluation procedures: R^2 correlation, average line length, and total footprint. The first two required Axial Line techniques while the last one consists of a simple area calculation.

3. Experiment Outcome

The evolutionary system was run with a population of 100 street patterns, for a total of 10,000 births. Street patterns with very low total footprints were first filtered out, resulting in 5500 remaining street patterns. A scatter-plot was created where each point represents a different street pattern. For the scatter plot, the R^2 *correlation* was plotted against *average line length*. The scatter plot is shown at the centre of Figure 3. Dark circles represent street patterns with larger total footprints, while light circles represent street patterns with smaller total footprints.

In the scatter plot, the most desirable area is the top-left corner, where the average line length is minimised and the R^2 correlation is maximised. The closer a point is to this area, the higher its rank. Conversely, the further away they are from this area, the lower their rank.

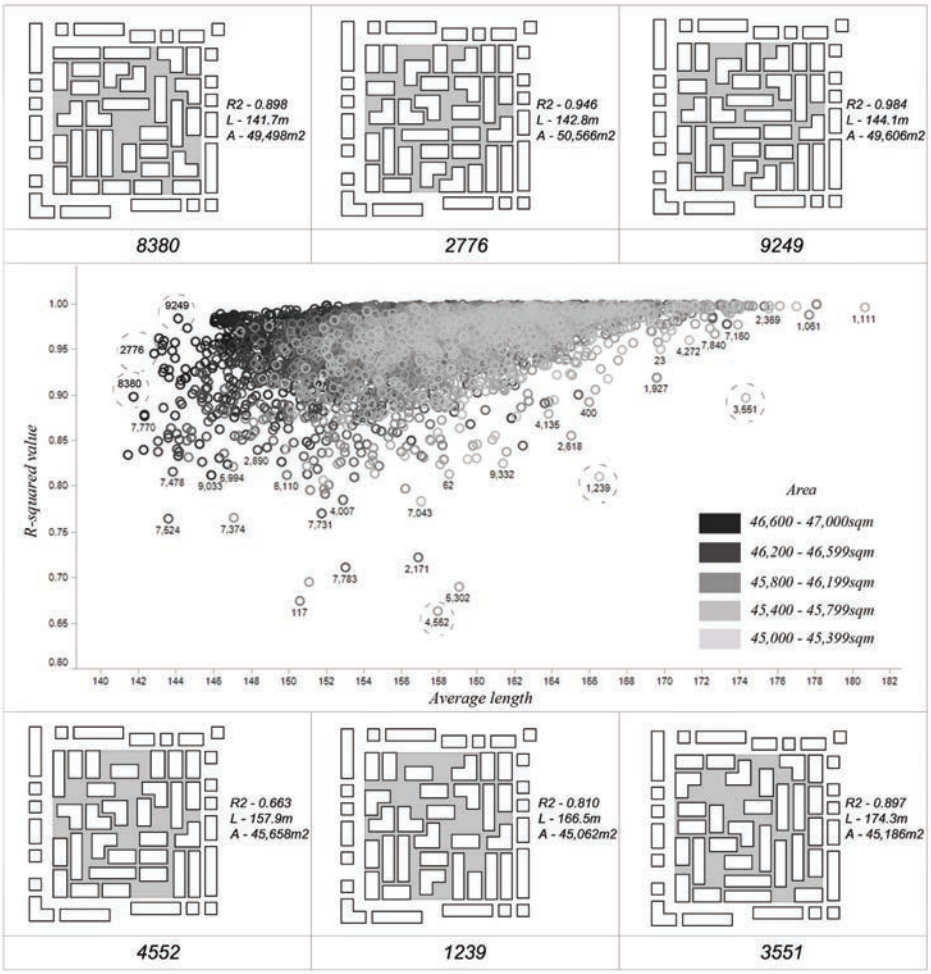

Figure 3. Scatter plot of 5500 individuals.

Various street patterns were selected to be examined in more detail. Figure 3, the three street patterns at the top have a high rank while the three street patterns at the bottom have a low rank. At first sight, it is hard to tell why one set would be more highly ranked than another set. However, certain key characteristics can be identified.

In general, the high rank street patterns have grid-like configurations where the urban blocks are evenly distributed and densely packed, thereby resulting in a high total footprint. They typically include a number of long, straight streets. These make the journey from one end of the street pattern to the other end easier as more

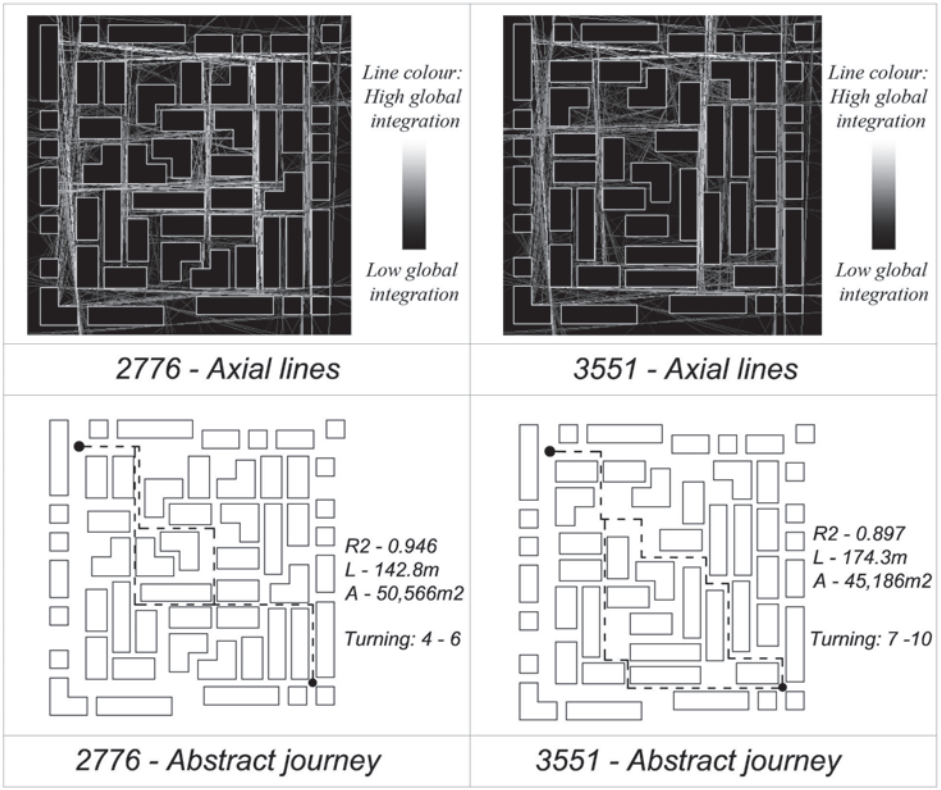

Figure 4. (a) Individual 2776 (b) Individual 3551.

direct routes can be used. The locations of open spaces are more well defined and easily accessible (Figure 4a).

In contrast, the low rank street patterns exhibit a more random configuration. The urban blocks are tightly packed in some areas and loosely distributed in other areas with some large open spaces in-between, thereby resulting in a low total footprint. This makes the journey from one end to another more complex (Figure 4b).

Overall, the highly ranked street patterns seem to have a more legible spatial pattern as compared to the lower ranked street patterns. This represents one phase in the evolutionary exploration process. Subsequent phases would tweak the generative technique in order to generate street patterns that differ more significantly with regards to R^2 correlation and average line length. In particular, increasing the block library to include a wider variety of urban blocks may result in more tightly interlocking patterns.

4. Conclusions

This paper has demonstrated how evolutionary algorithms can be used to link generative modelling techniques to Axial Line evaluation techniques. This suggests an alternative explorative design method for the early phases of urban design, when overall urban patterns and textures need to be developed. Future research will further develop this design method taking into account a wider range of performance criteria, including in particular environmental criteria such as solar radiation and daylight.

References

Al_Sayed, K.: 2012, A systematic approach towards creative urban design, *Proceedings of the 5th International Conference in Design Computing and Cognition (DCC'12)*, College Station, TX.

Battle, G., and McCarthy, C.: 1994, Multi-source synthesis: Intelligent Cities – A Climate for Change, *Architectural Design*, **66**(9/10).

Bentley, P. J. (ed.): 1999, *Evolutionary Design by Computer*s, Morgan Kaufmann, San Francisco, CA.

Bentley, P. J. and Corne, D. W. (eds.): 2002, *Creative Evolutionary Systems*, Academic, London.

Braach, M. and Friz, O.: 2010, The Organisation of Plots, *in* Hovestadt, L. (ed.), *Beyond the Grid – Architecture and Information Technology*, Birkhauser, Berlin, 24–31.

Caldas, L.: 2001, *An evolution-based generative design system: using adaptation to shape architectural form*, PhD. Dissertation, Massachusetts Institute of Technology, Cambridge, MA.

Caldas, L., and Rocha, R.: 2001, A Generative Design System Applied to Siza's School of Architecture at Oporto, *Proceedings of the 6th CAADRIA Conference*, Sydney, Australia, 19–21.

Canuto, R.: 2012, Establishing parameters for urbanity, *Proceedings of the 8th International Space Syntax Symposium*, Santiago, Chile.

Chen G., Esch G., Wonka P., Müller P. and Zhang E.: 2008, Interactive Procedural Street Modeling, *Journal of ACM SIGGRAPH 2008*, **29**(3).

Duarte, J. P., Ducla-Soares, G. and Caldas, L. G.: 2006, An Urban Grammar for the Medina of Marrakech: Towards a Tool for Urban Design in Islamic Contexts, *Proceedings of the 3rd International Conference on Design Computing and Cognition DCC'06*, Atlanta, GA, 483–502.

Frazer, J. H.: 1995, *An Evolutionary Architecture*, AA Publications, London, UK.

Hanson, J.: 1998, *Decoding Homes and Houses*, Cambridge University, Cambridge, UK.

Hillier, B. and Hanson J.: 1984, *The Social Logic of Space*. Cambridge University, New York.

Hillier, B.: 1996, *Space is the Machine*, Cambridge University, Cambridge, UK.

Hillier, B.: 2002, A theory of the city as object: or, how spatial laws mediate the social construction of urban space, *Journal of URBAN DESIGN International*, **7**,153–159.

Hillier, B., Stonor, T. and Karimi, K.: 2008, Using Space Syntax to regenerate the historic centre of Jeddah, or why we need architectural models of cities, *Proceedings of UIA World Congress: Tools for governance*, Turin, Italy.

Janssen, P.: 2004, *A design method and computational architecture for generating and evolving building designs*, PhD Dissertation, School of Design, Hong Kong Polytechnic University.

Janssen, P., and Chen, K. W.: 2011, Visual Dataflow Modelling: A comparison of three systems, *Proceedings of CAAD Futures '11*, 801–816.

Janssen, P., Basol, C. and Chen, K. W.: 2011, Evolutionary Developmental Design for Non-programmers, *Proceedings of the 29th eCAADe Conference*, University of Ljubljana, Slovenia, 245–252.

Janssen, P. and Kaushik, V.: 2013, Decision chain encoding: Evolutionary design op-timization with complex constraints, *Proceedings of the 2nd EvoMUSART Conference*, Vienna, Austria, 157–167.

Ostwald, J. M.: 2011, Axial Line Analysis Revisited: Reconsidering its Value for Architecture, *The International Journal of the Constructed Environment*, **1**(3), 219–242.

Parish, Y. I. H. and Muller, P.: 2009, *Procedural Modelling of Cities*, Research Report, Department of Computer Science, Purdue University, USA.

Stonor, T.: 2009. "Measure, map, model, make". Available from Space Syntax official website: <http://www.slideboom.com/presentations/615318/Tim_Stonor_Measure-map-model-make> (accessed 6 September 2012).

Turner, A., Penn, A. and Hillier, B.: 2004, An algorithmic definition of the axial map, *Environment and Planning B: Planning and Design*, **32**(3), 425–444.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 705–714. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

SKELETAL MODELLING

A developmental template for evolutionary design

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Abstract. Evolutionary design is an approach that evolves populations of design variants through the iterative application of a set of computational procedures. For architecture and urban design, the developmental procedure typically needs to be capable of generating bounded variability, whereby design variants are both highly variable and highly constrained. This paper proposes a template for creating such developmental procedures. The template uses decision chain encoding techniques in order to generate a sparse skeleton model, and then uses standard parametric modelling techniques in order to generate a detailed form model. A demonstration is presented where the template is used to create a developmental procedure for generating design variants for a large residential project.

Keywords. Evolutionary; developmental; generative; design optimisation.

1. Introduction

Evolutionary design (Frazer, 1995; Bentley, 1999; Caldas, 2001; Bentley and Corne, 2002; Janssen, 2004) is an approach that evolves populations of design variants through the iterative application of a set of computational procedures. The developmental procedure generates design variants, one or more evaluation procedures assess the performance of design variants, and the feedback procedure drives the evolutionary process by applying selective pressure to the population. The selective pressure is applied by ensuring that design variants with low performance scores are more likely to be killed, while design variants with high performance scores are more likely to survive, and to be selected for reproduction.

The terminology is loosely based on the way that these terms are used in biology (Mahner and Kary, 1997). A *gene* is a variable that can have different values (sometimes referred to as *alleles*, but typically ‘gene’ is used to refer to both the

variable and the value). The expression of an individual's gene values will give rise to observable characteristics or traits, referred to as *phenes*. The *genotype* of an individual is the set of gene values, while the *phenotype* of an individual is the set of phene traits. The *genome* describes the set of all possible genotypes in the population, while the *phenome* describes the set of all possible phenotypes in the population.

From a design perspective, the phenome describes the set of possible design variants. These variants will differ from one another with regards to their phenes, but they will also share a certain common identifiable character. The formative design model can be defined that describes both the variable and common characteristics of a design, referred to as a *design schema* (Janssen, 2004). The design schema represents a specific idea or strategy for tackling a particular design scenario. For an evolutionary design approach, the design schema needs to be encoded in the development, evaluation, and feedback procedures used by the evolutionary process. Although all three procedures are affected by the design schema, the developmental procedure is the one with the most direct impact as it is the procedure that actually generates design variants.

This paper will focus mainly on the developmental procedure. A template for creating developmental procedures is proposed that helps to overcome certain key issues related to noise and epistasis. A demonstration is presented where the template is used to create a developmental procedure for generating design variants for a large residential project.

Section 2 describes the developmental template, section 3 presents the demonstration, and section 4 briefly draws conclusions and indicates avenues of further research.

2. The Developmental Procedure

The developmental procedure generates a phenotype, which in evolutionary design is a design variant. This procedure is also referred to as an *embryogeny* (Bentley and Kumar, 1999) or as a *decoder function* (Eiben and Smith, 2003, pp. 216-217). The phenotype is generated under the influence of the genotype and the environment. For the genotype, the values of the individual genes will be linked to parameters in developmental procedure. For the environment, features in the environment such as the site boundary or other types of data such as weather data will be used within the developmental procedure (Frazer, 1995).

The mapping between genes and phenes can range from being highly direct to highly indirect. An example of a highly direct mapping could be a gene that controls a dimensional parameter in a model of the phenotype. An example of a highly indirect mapping could be a gene that defines a parameter in an iterative growth

rule (such as the cellular automata rule) that gets triggered repeatedly together with other rules to generate the phenotype.

The main weakness of direct types of mappings is that they result in a phenome with very limited design variability. In order to increase variability, more indirect mapping techniques need to be used. However, such indirect mapping techniques can result in highly complex non-linear search spaces that may significantly hinder the progress of the evolutionary search process. In particular, two key issues are identified that add complexity to the search space: noise and epistasis.

The issue of noise relates to the fact that as mappings become more indirect, they tend to produce a higher proportion of invalid designs (Janssen, 2004). The reason is that with a higher level of indirection, it becomes harder to appropriately constrain the developmental procedure to only produce valid designs. Invalid designs may then quickly start to dominate the population, thereby adding a high level of noise to the search space.

The issue of epistasis relates to the fact that as mappings become more indirect, they tend to have genes with a higher level of epistasis. Epistasis is the phenomenon where the effects of one gene are modified by one or several other genes. Developmental procedures with a higher level of indirection tend to use complex rule based procedures, with a significant level of interaction between the rules. The resulting high levels of epistasis obfuscate the relationship between genes and phenes, thereby making the search space highly non-linear (Draghi and Wagner, 2008).

The aim is therefore to create a developmental procedure that results in a phenome with sufficient design variability while at the same time limiting noise and epistasis to the minimum. Phenomes for architectural and urban designs are typically both highly variable and highly constrained. They are highly variable in the sense that there is no fixed organisational plan, but instead entities can be organised in space in a wide variety of ways. At the same time, these organisations are highly constrained by various rules delineating the validity of possible designs. This type of phenome that is both highly variable and at the same time highly constrained is described as having *bounded variability*.

2.1. THE DEVELOPMENTAL TEMPLATE

For phenomes displaying bounded variability, a template for creating developmental procedures is proposed that uses an intermediate skeleton model. The proposed template, shown in Figure 1, consists of two stages: skeleton generation followed by form generation.

The skeleton generation stage starts with a base model that contains fixed elements of the design not subject to evolution. A skeleton model is then constructed

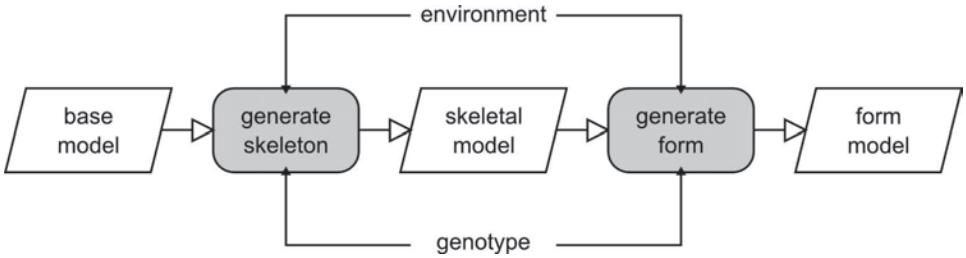

Figure 1. The template for developmental procedures.

that represents the overall form of the design. The skeleton model may consist of basic geometric elements with attributes that add semantic labels. The form generation stage starts with the skeleton model and then constructs form around the skeleton, using the geometric elements and attributes as a guide. Both skeleton generation and form generation can be influenced by the genes in the genotype or by features in the environment.

The skeleton model is a minimal three-dimensional structure that is lightweight and sparse while the form model is a more detailed model that may be large and complex. However, the skeleton generation process typically has to deal with more complex constraints, and as a result this process also tends to be more complex than the form generation process.

For the skeleton generation process, an encoding technique has been defined called *decision chain encoding* (Janssen, 2004; Janssen and Kaushik, 2013). The key feature of this encoding technique is its ability to control variability by handling complex sets of constraints, thereby minimising noise. In addition, certain techniques are suggested to limit the disruptive effects of epistasis.

2.1.1. Decision Chain Encoding

The decision chain encoding technique structures the skeleton generation process as a sequential chain of decision points. Each decision point involves choosing one option from a list of options. The list of options is created by a set of rules that generate and filter options. The genotype consists of a list of real-valued genes in the range {0,1}. For each decision point, a gene will be used to select an option by mapping it to an integer value in the range {0,n-1}, where n is equal to the total number of valid options for that decision point. Note that for each decision, the total number of valid options may not be known and may depend on the previous decisions.

With regards to noise, the decision chain encoding technique allows design variability to be carefully controlled. This allows a wide variety of valid design

variants to be generated, while at the same time avoiding the creation of invalid designs.

With regards to epistasis, it is noted that with the decision chain encoding technique, a gene is not epistatically linked to any of the genes used earlier in the decision chain (since the options available at some earlier point in time are not affected by the current decision), but is likely to be epistatically linked to many of the genes used later in the decision chain (since the options available at a later point in time may be affected by the current decision). This suggests that such genotypes will have a mixed level of epistasis, with some genes having high epistasis and other having low epistasis.

3. Demonstration

In this section, the implementation of a developmental procedure for a complex building configuration is described, and a set of design variants are presented as examples of the types of forms that can be generated. The process of evolving design variants using this developmental procedure is not described in this paper.

3.1. THE DESIGN SCHEMA

The design scenario for the demonstration is for a medium-rise residential project consisting of blocks of flats. The design schema uses a "staggered brick" pattern, where rectangular building blocks consisting of multiple floors are stacked up on top of one another in a brick pattern. The design schema is loosely based on a set of recent projects that have used variants of the staggered brick patterns: the OMA's Interlace project (The Interlace/OMA, 2013), the Celosia Residence MVRDV project developed in collaboration with Blanca Lleó (Celosia Building/MVRDV, 2013), the Bjarke Ingels Group Taipei City Wall project in Taiwan (Taipei City Wall/BIG, 2013), and the A-Lab Statoil project in Oslo (Statoil/A-Lab, 2013).

For the proposed design scenario, the design schema consists of a set of blocks of four different types, each between 4 to 8 stories tall. The blocks are stacked in a staggered brick pattern, and each stack of blocks is rotated around a pair of vertical axes, creating a complex interlocking configuration. The axes of rotation coincide with the location of the vertical cores of the building, thereby allowing for a single vertical core to connect blocks at different levels. The blocks are almost totally glazed, with large windows on all four facades. In addition, blocks also have a series of shades projecting out from the façade. An example is shown in Figure 2, where 7 blocks are stacked and rotated to form an interlocking configuration.

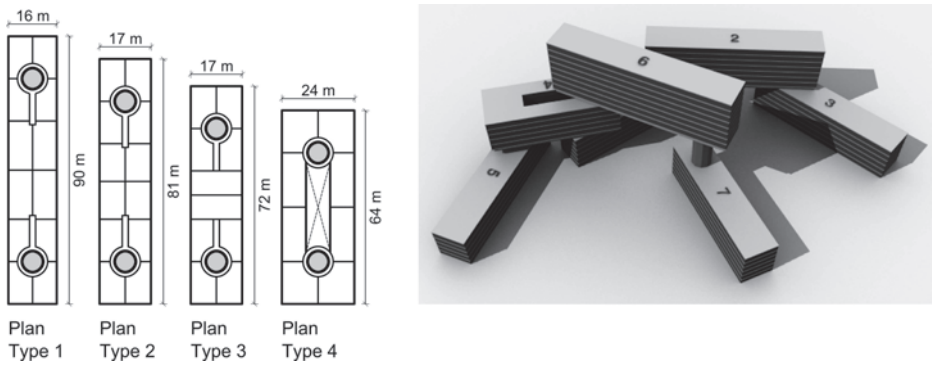

Figure 2. The four plan types and an example of how these plan types can be combined into a staggered brick configuration. In the model, the number on the block indicates the order of placement.

Three evaluation procedures are defined. The window daylight procedure calculates the number of windows receiving daylight below a certain minimum threshold on an overcast day. The façade cost procedure calculates the cost of the façade, including glazing systems and shades required to bring the heat gain through the facade to below a certain minimum threshold (Janssen and Kaushik, 2012). The core length procedure calculates the total vertical core length, representing lifts and other services. (This also acts as the penalty function for high buildings.) All three performance measures need to be minimised.

3.1.1. Hard and Soft Constraints

When generating design variants, a number of hard constraints have to be satisfied:

- The total floor area of the blocks must remain constant, based on the plot ratio of the site.
- The blocks must be positioned within the site boundary, including a setback of 10 meters.
- The blocks must be positioned so that a minimum horizontal spacing of 10 meters is maintained between blocks.
- The angle of rotation for adjacent blocks must be selected from a set of predefined angles (for example, 15, 30, 45, 60).

In addition to these hard constraints, one key soft constrain also has to be considered related to the height of the building. This soft constrain was added after initial experiment revealed that many of the design variants were unrealistically

high. In the developmental procedure, the height of the building is only increased if no other options are available, thereby giving preference to low designs over high designs. In addition, the core length evaluation procedure is added that penalises very high buildings.

3.2. SKELETON GENERATION

The skeleton generation process uses a decision chain encoding technique in order to control variability. The skeleton model represents each block as a single longitudinal line at the base of the block that joins the centres of the two cores. Each line has attributes that define the block type and the block height. The skeleton model is therefore highly simplified, typically consisting of 20 or 30 lines floating in space.

The block lines are positioned within the site volume one after another. The placing of the block lines involves three decisions: choosing the block location, choosing the block type, and choosing the block height. The decision chain therefore consists of a sequence of block placing steps, where each step consists of three sequential decisions.

- The location choice decision requires a list of location options in space to be calculated. This consists of three stages: first, all locations are calculated based on the positions of the cores already placed; second, valid locations are obtained by filtering out all invalid locations that break any of the above mentioned hard constraints; third, the remaining valid locations are filtered according to soft constraints, by giving priority to lower locations over higher locations.
- The block type decision requires a list of block type options to be calculated. In total, there are four block types. However, due to the differing sizes of the blocks, they may not all fit in the chosen location. Therefore, the block type options are calculated by filtering out all invalid block types that break any of the above mentioned hard constraints.
- A block height decision requires a list of block height options to be calculated. Block heights may vary between 4 and 8 stories, assuming there is sufficient space. The block height options are calculated by filtering out all invalid block heights that break any of the above mentioned hard constraints.

Once all three decisions are taken, a new block line is then inserted into the model, and the process is repeated until the required floor area is reached.

3.3. FORM GENERATION

Once a skeleton model consisting of block lines has been generated, the form model can then be generated using standard parametric techniques. The process consists of three steps: creating blocks, creating cores, and creating facades. None

of these three steps make use of any genes in the genotype. The first two steps also do not require any data related to the environment. Only the third step is influenced by the environment, as weather data is required.

- For the block creation step, a parametric model of each of the four block type is created, with the parameter being the number of floors. The block lines in the skeleton models are then replaced with the appropriate block models, with the floors parameter being extracted from the block line attribute.
- For the core creation step, the endpoints of the block lines indicate the positions of the cores. For each set of vertically aligned core points, a core is inserted, starting at the ground and ending at the highest point.
- For the façade creation step, the depths of the sunshades need to be defined and glazing systems need to be selected in order to reduce the heat gain to below a certain threshold. A a set of simulations are executed in order to calculate cumulative solar radiation on each windows for a period of a whole year and these values are then used to define sunshade depths and to select glazing systems.

3.4. GENOTYPE STRUCTURE

The genotype consists of a set of genes specifying global variables and a set of decision. All genes are real-valued numbers in the range {0,1}.

When considering the genotype structure, two issues need to be addressed. The first is how to organise the genes for the three types of decisions. One approach is to simply list all the genes in one long genotype, following the sequence of decisions. However, this means that a crossover operation would only always affect all three types of decisions. For example, it would not be possible to crossover only the block type decisions while leaving the other types of decisions the same as before. The genotype is therefore structured as four separate chromosomes: chromosome 1 is used for global variables, chromosome 2 is used for location choice decisions, chromosome 3 is used for block type decisions, and chromosome 4 is used for block height decisions. Chromosome can then be crossed over independently from one another.

The second issue to be addressed when considering genotype structure is the fact that the total number of decisions that need to be made is not known in advance. The number of blocks depends on which block types and block heights are chosen. For example, if large high blocks are chosen, then the maximum floor area will be reached with fewer blocks, and therefore fewer decisions need to be made. In order to deal with this uncertainty, the chromosome lengths are defined based on the maximum number of decisions that could be required. This means that genes at the end of the chromosome are redundant in cases where the required floor area is achieved before that maximum is reached.

3.5. DESIGN VARIANTS

The developmental procedure is able to generate a vast variety of design variants with significant variations in performance. Figure 3 shows three randomly generated design variants for a site in Singapore. The total built floor area for all three variants is 226,000 meters squared, which results in close to 1500 flats.

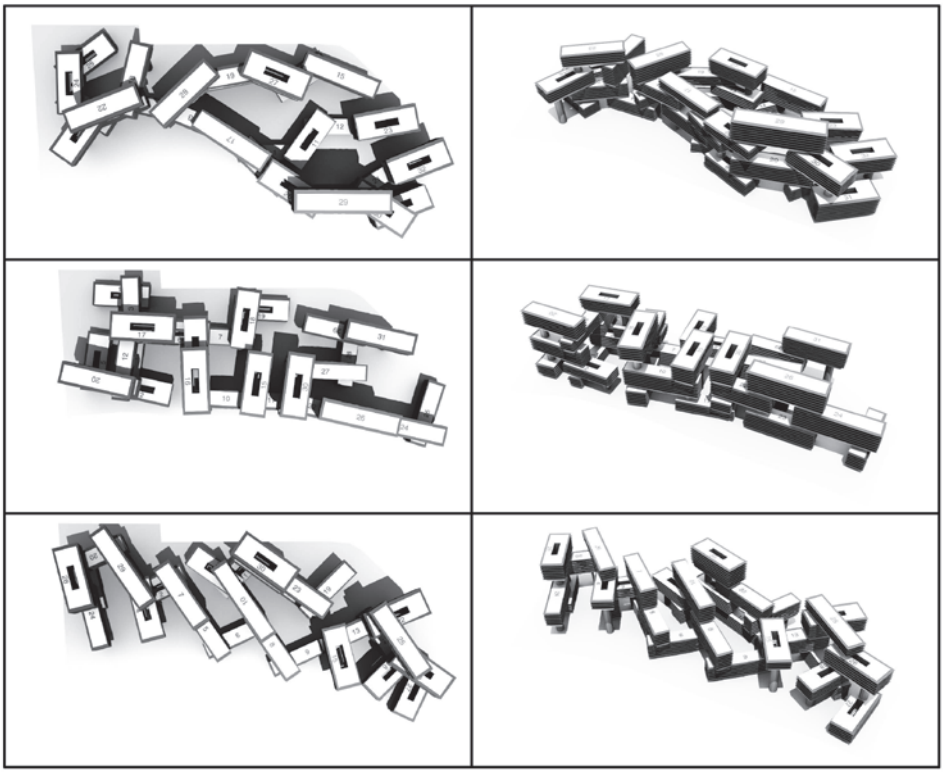

Figure 3. Three design variants.

4. Conclusions

A developmental template has been proposed for phenomes that display bounded variability. The template uses decision chain encoding techniques in order to generate sparse skeletons of design variants, and then uses standard parametric modelling techniques in order to generate models of the final forms.

Future research will further investigate the use of decision chain encoding techniques, focusing in particular on the issue of epistasis. Strategies for minimising

the disruptive effects of epistasis have been proposed but have so far not been validated. Initial experiments have been conducted, where designs have been successfully evolved using decision chain techniques (Janssen and Kaushik, 2013), but further experimental data is required in order to substantiate these results.

References

Bentley, P. (ed.): 1999, *Evolutionary Design By Computers*, Morgan Kaufmann, San Francisco, CA.

Bentley, P. and Corne, D. (eds.): 2002, *Creative Evolutionary Systems*, Morgan Kaufmann, San Francisco, CA.

Bentley, P. and Kumar, S.: 1999, Three ways to grow designs: a comparison of evolved embryogenies for a design problem, *Proceedings of the Genetic and Evolutionary Computation Conference*, Morgan Kaufmann, 35–43.

Caldas, L. G.: 2001, An evolution-based generative design system: using adaptation to shape architectural form, PhD Dissertation, Massachusetts Institute Of Technology.

"Celosia Building/MVRDV": 2013, Available from: Open Source Repository < http://www.archdaily.com/29637/celosia-building-mvrdv-with-blanca-lleo/> (accessed 17 February 2013).

Draghi, J. and Wagner, G. P.: 2008, Evolution of evolvability in a developmental model, *Evolution: International Journal of Organic Evolution*, **62**(2), 301–315.

Eiben, A. E. and Smith, J. E.: 2010, *Introduction To Evolutionary Computing*, Springer.

Frazer, J.: 1995, *An Evolutionary Architecture*, AA Publications, London.

Janssen, P. H. T.: 2004, A design method and computational architecture for generating and evolving building designs, PhD Dissertation, The Hong Kong Polytechnic University.

Janssen, P., Chen, K. W. and Basol, C.: 2011, Evolutionary developmental design for non-programmers, *Proceedings of the 29th eCAADe Conference*, Ljubljana, Slovenia, 245–252.

Janssen, P. and Kaushik, V.: 2012, Iterative refinement through simulation: exploring trade-offs between speed and accuracy, *Proceedings of the 30th eCAADe Conference*, Prague, Czech Republic, 555–563.

Janssen, P. H. T. and Kaushik, V.: 2013, Decision chain encoding: evolutionary design optimization with complex constraints, *Proceedings of the 2nd EvoMUSART Conference*, Vienna, Austria, 157–167.

Mahner, M. and Kary, M.: 1997, What exactly are genomes, genotypes and phenotypes? and what about phenomes?, *Journal of Theoretical Biology*, **186**(1), 55–63.

Michalewicz, Z.: 1996, *Genetic Algorithms + Data Structures = Evolution Programs*, Springer, Berlin.

"Statoil/A-Lab": 2013. Available from: Open Source Repository < http://www.archdaily.com/166664/in-progress-statoil-a-lab/> (accessed 17 February 2013).

"Taipei City Wall/BIG": 2013, Available from: Open Source Repository < http://www.big.dk/#projects-wall> (accessed 17 February 2013).

"The Interlace/OMA": 2013, Available from: Open Source Repository < http://www.archdaily.com/34142/the-interlace-oma/> (accessed 17 February 2013).

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 715–724. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

SPACE EMERGENT FIELD

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Abstract. Architecture has always been founded upon ideologies. However could the influence of human interactions create a new perspective for space form evolution? To create a spatial adaptive system, to the influence of culture and behaviour of human being? The output of this spatial system is the determination of optimised values for spatial configurations by biomolecular, self-assembly computation for emergent spatial forms.

Keywords. Spatial; adaptive; biomolecular computations; self-assembly.

1. Introduction

The design process stems from having a clear and comprehensive design brief. This contains a set of requirements and statements of the intended use of the building to fulfil the activity tasks within. It is the skill / experience of the designer to interpret the brief into a design solution, the concept. This approach has no supporting tools to test or validate the design solution. However this is in contrast to the sciences where sequences assessment points are defined, evaluated to determine if results meet objective aims. At the 'end of this process, the analyst has to interpret and obtain some conclusions' (Cobo et al., 2011). This is performed by software tools by extraction of data, to discover possible positive synergies. This form of analysis is in contrast to the design process. 'The designer's greatest gift, his intuitive ability to arrange physical form, is being reduced to nothing by the size of the task in front of him' (Alexander, 1964). This coupled with the technical application to form a problem solving direction is undermined by the ever increasing amounts of data, by the functional requirements of standards, codes, specification to give regulation conformity. It is this complexity that will mask, shroud and obscure the direction of design process. 'Unlike other design fields where targets are set to solve a particular problem in the best possible way, architectural design is open-ended' (Terzidis, 2006). In this environment the designer will revert to past experiences and

knowledge to identify the final solution as ‘the end of the design process requires experience and judgment’ (Lawson, 2006).

The aim of the research, can there be progression of the design process to enable spatial arrangement creation by the influence of:

- Human interactions by regional cultural adaptation.
- Optimisation by critical evaluation by autonomous computation.

2. Spatial Change

Architectural design is influenced by current tastes, fashion or style to model our buildings to suit the current trends of the day or display wealth to others to meet society expectations. Sociological fashion may change ‘like the continuously changing arrangements of office furniture governed by the market forces at work in high-rise buildings’ (Reiser et al., 2006). However these arrangements of spatial activities in the ‘built environment are dominated by two types of spatial organisation: the open plan and the corridor / cellular room arrangements. Both are defined by a specific attitude’ (Hensel et al., 2006). This attitude is intrinsically linked to the building typology, the function of the building, whether a theatre, school, hospital or office. These space activity arrangements within a building are predetermined forming the correlationship to the building function – the typology. This building typology creates a systemised architectural design that is the fundamental basis and principle of current design thinking.

Architectural theorist Kwinter (2001) describes current building approaches to architectural style and theory in the modern age, as being lost and without direction, as he refers to this as formalism. ‘A sloppy conflation of the notion of form with that of object.’ May it be possible to consider another design process path: to go beyond the current thought to one without preconception, to give evaluation and imagination based upon what is present rather than, what may be tailored to fit? To employ strategies as a logic system to comprehend and enable understanding in addressing complex design objectives? The creation of a new design pathway to form spatial awareness to the application of the brief, with human beings at its centre. To enable movement away from the reliance of standardisation of the solution by designers.

3. Spatial Devision – Current Space Methodology

Architectural design is influenced by a pre-defined morphology, set by spatial standards and relationships as defined, described and imposed by the A J metric Handbook, ‘Metric sizes indicated throughout this handbook do not necessarily imply dimensional standards for actual objects or furniture shown, but refer

generally to the space required to accommodate them within the overall design.' (Fairweather, 2008). The determination of the defined space activity is broken down into the following criteria:

- Introduction of controlled environmental conditions on the design.
- Best functional metric dimension [size] for the new design.
- Design need to be dimensionally co-ordinated with other units.
- Overall dimensioned pattern from the activity point of view.
- Controlled dimension the product should conform to.
- What range of module sizes are required.

This source of standardising to define space in a two dimensional form of activity space is self-limiting, as this suggests people throughout the globe have no social differences between them and the environments which they are placed are without contrast. Anthropologist Edward Hall of MIT in 1966 studied and defined spaces by cross cultural communication reaction of differing cultural settings, social orders and behaviour patterns of humans being, to view how surrounding space was perceived by them, defined by the Theory of Proxemics – the study of the human use of space within the context of culture.

It is this loss of connection to the human being by standardisation and loss of contact with our surrounding which is not reflected in nature. Nature's biosystems have the ability to adapt to changing environmental condition and control material composition. These are evolving systems as they learn, defend, communicate, and protect themselves by the mechanisms of synergy to environmental influence. Nature uses these mechanisms in an evolutionary perspective of actions to give adaptable strategies. Our 'planet is not inanimate. It is a living organism. The earth, its rocks, oceans, atmosphere and all living things are one great organism. A coherent holistic system of life, self-regulating, self-changing' (Lovelock, 1991).

3.1. AUTOCHTHONOUS: A NEW UNDERSTANDING OF DIFFERENCE

The question: Can cultural setting shape spatial arrangements for human habitation? To give true connection to the spaces humans inhabit to enable any sustaining kind of authentic culture in the future, will depend ultimately on our capacity to generate vital forms of regional culture and civilisation. Hall (1976) describes cultural space as a ' organising frame for space as a system of communication, and for spatial aspects of architecture and city planning'. This cross cultural communication is communication and communication is culture and it is this human interaction and their environment participates in moulding each other was described by Hall. Humans have the ability of creating the cities in which we live, to determine the spaces that define interactions, contact and communication

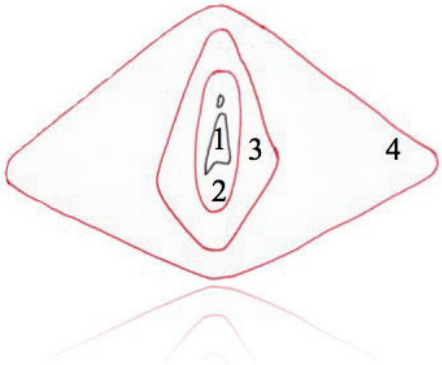

Figure 1. Reaction bubbles by Hall.

between us all. This perception of space of how peoples requirements are influenced by their environment is controlled by the human sensory system. The feeling of discomfort, that is afforded to interactions between cultures and individuals, was defined by Hall into four areas called the reaction bubbles. These spaces are defined as intimate, personal, social and public spaces, as indicated by Figure 1.

- 1 – Intimate space: defined 0.46 – 1.2 metes. Closeness of proximately space to connection with another, that is given or enforced upon by social requirement: circulation space queuing, transportation- lifts, trains, aviation.
- 2 – Personal space: defined 0.61 – 1.2 metes. Spatial zone afforded to first contact with another for whom the individual is not known – social requirement: meetings, introductions, social engagement – restaurants.
- 3 – Social space: defined 1.2 – 2.7 metes – close phase, defined 2.1 – 3.7 metes – far phase. The distance of formality and impersonal contact between another for communication and contact – social requirement: Business, formal meetings.
- 4 – Public space: defined 3.7 – 7.6 metes – close phase, defined 7.6 > – far phase. Limited interconnection between individuals or groups.

Hall (1976) further investigated the sense and pattern of spatial understanding as ‘the sense of space is moulded and patterned by culture’. He investigated the Arab understanding of space and compared it to the European perspective. An Arabian home avoids the division of space by walls as the culture does not wish to remain by themselves. This culture has a high sensitivity to crowding, this view and understanding is not representative in the US model, which suffers accordingly by the movement towards defining human space relationship by structured forms and the importance of culture is minimised.

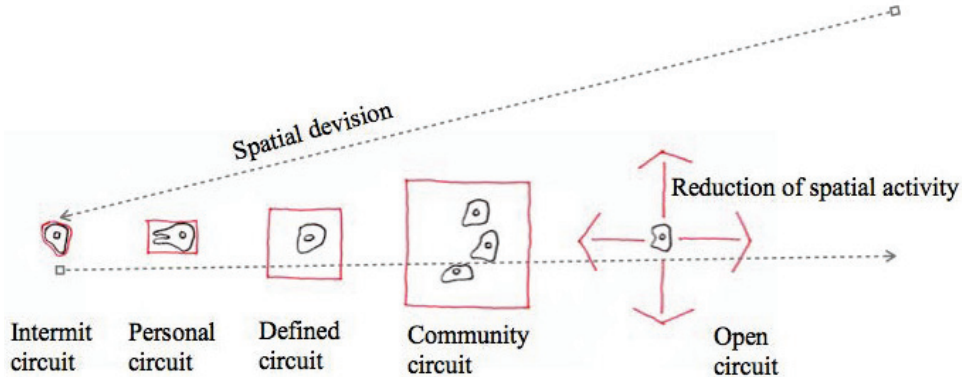

Figure 2. Definition of space to activity function.

The hidden dimensional field creates the framework defining and organisation of space that changes dependant upon pattern of cultural, social setting and knowledge of a individual – the evaluation of a new understanding of difference to human space perception.

That if applied incorrectly may lead to failure of communication and status. Hall further investigated the influence upon fixed and semi-fixed spaces, halls with furniture arrangements, building and cities giving differing understanding and expectations upon the human senses. Could this extension to expand social science of collective consciousness be embraced within the creation of the spaces we inhabit to give a human sense of space?

To expand the current understanding of the definition of space to activity function use by convention – A J metric. Figure 2 defined functional space activity by convention.

- Intimate circuit: defined per individual: theatre seating – 0.375sqm, AJ metric handbook, 10 person passenger lift – 0.182sqm Stannah lifts, Aircraft passenger seating 0.40sqm – European Aviation Safety Agency, rail travel – 0.25sqm Southwest trains. A spatial pattern to form arrangement – theatre seating, transportation, etc.
- Personal circuit: defined per individual: Restaurant and bar table – 0.96sqm AJ metric handbook, reading / study seat- plus area around for using it- 1.39 to 2.78sqm – computer work station – plus area around for using it – 1.85 to 5.57sqm depend upon type of use, short term, long term, individual or group (Erikson et al., 2007).
- Defined circuit: close contact to give intimate connection to the task activity – example Nursery provision – Children < 2yrs – 3.5sqm per child, Child at 2yrs – 2.5m2 per child, Children 3 to 5yrs – 2.3sqm – (DfEE Section 337: Day Nurseries, 1999).

- Community circuit: defined – cultural communication, example community halls. Spatial need of human interaction and connections to form activity – event spaces, congregation, social gathering, courtyards, squares – Piazza del Campo Siena.
- Open circuit: defined, separation of human interaction for activity connection to the landscape.

4. Evolving Spatial Circuit

Could a cumulative relationship of the two spatial systems achieve spatial optimal values to enable movement to facilitate an embryological approach to combine the two spatial systems (spatial proxemics + defined space active behaviour) as a singularity, a blue-print to a generative engine to absorb the two systems, to form a new understanding of spatial functional creation?

- To develop a new spatial codification system of the understanding of the specific and defined requirements to form a 'reservoir of architectural species' in a new 'genetic pool' (Zaera-Polo et al., 2004).
- To find relationship linkages between humanism and form to give a sense of connection to the spaces we inhabit. May this new understanding of generative species enable an evolving resilient new human spatial order. 'A long awaited paradigm shift, occurred not in the designers mind but in the creation of this new codification of the design process' (Terzidis, 2006).

To enable integration of two seemingly contrasting worlds of culture and the defined fixed spaces to give generative species development of the current building typology. This combinational system could give systematic connectivity to the human senses, to enable movement away from the reliance of standardisation of the solution (Figure 3).

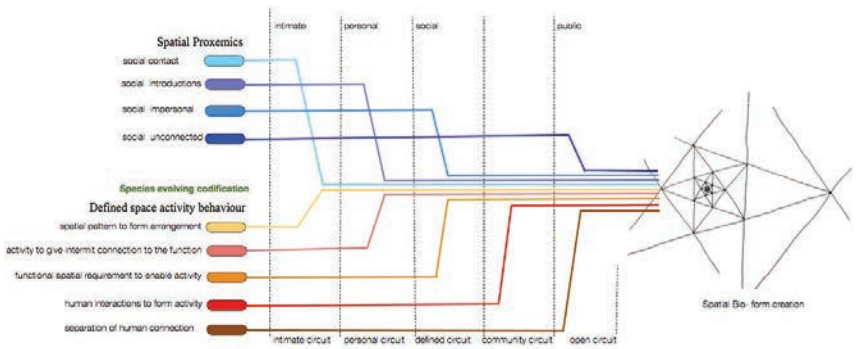

Figure 3. Schematic model.

Could this evolving species based upon quantifiable data, form a new codification system based upon collective mathematical data solution analysis. This new design pathway, a route map of creative form finding, as a combinatory solution binding the social sciences and defined space activity behaviour. The aim to enable a new generative spatial mechanism to drive design solution evolution, by the approaches of human interaction.

Objective:

- 1. To gain encoded values inputs between the two spatial systems as defined in Figure 3.

5. Genetic Algorithms as a Computational Technology

Defining architectural forms by current computations has focused upon geometric proportional rules, arrangements of activity spaces functions within the building and the technology use to construct it. This has been achieved by building complex 3D forms by starting with a limited number of primary geometric shapes, for example: pyramids, wedges, blocks. Eastman and Henrion (1977) used these principles to develop Glide. Their research was to investigate if the application of algorithmic processes could create self-replication as an expression of form development to enable application. Glide analysed this task by forming three levels of hierarchy to determine a 3D form, based upon the primary geometric shape of a polyhedron. These three hierarchical elements are: Image, Shape and Object. The knowledge of the assembly for the construction of the various edges and folds, that governed their behaviour was achieved by halfedges using the Euler Operator to form shape creation, under the umbrella of Unix®.

However could the objective be: ultimately building not from solid modelling as an abstract solid form, but as a collection of voids enclosed by surface. These voids could contain the encoded spatial value functions in determining the spatial surfaces around, by the application in the developments of DNA computation.

6. Biomolecular Computing Systems

Biomolecular computations are methods for executing programming of DNA by systems and software tools that aid the design, verification and simulation by using DNA as engineering material. DNA has the ability to self-assemble and execute operations autonomously by encoded sequences of strands to form DNA nanostructures.

The manipulation of DNA to enable increasing functionality, communication, and control is achieved by interface sequence optimisation system, for designing

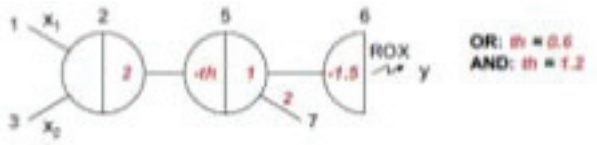

Figure 4. Abstract (taken from Qian and Winfree, 2011).

DNA nanostructures focused upon sequential Boolean computation. Figure 4 is an abstract of this, developed by the research of Qian et al. (2011). This abstract represents the process: x1 and x2 are the inputs to gate 2 and resultant output is feed into gate 5. The threshold level *th* determines the logic and makes the circuit compute the OR of x1 and x2 and while setting *th*=1.2 makes the circuit compute AND of x1 and x2. This sequential Boolean computation function of using purely operations of AND and OR 'are executed by seesaw gates, and restoration to the digital values is through thresholding gates followed by catalytic amplification of any leftover signal' (Chandran et al., 2011).

This Boolean function has been applied to form spatial configurations Chandran et al. (2011) in the creation of addressable reaction spatial network formations. Below are the simulation steps how this could be applied:

- Start initial spatial configuration of the system.
- Calculate the probability that the next event will be a ligation or restriction.
- Calculate the probabilities of various ligations and restrictions.
- Perform those events with the calculation probabilities.
- Update the configurations of the system and concentrations of the spatial patterns and follow link connection.

The reaction spatial network circuit output of this is the creation of autonomous executions of reactions in Figure 5. This example illustrates the Boolean function of x1. x2 + x3. x4 with the initial species highlighted in the darker boarder.

This computational sequence could process and help to solve complex problems in the field of architecture. This ability to form self-assembly by reaction networks to create structured and sequenced spatial arrangements at a nano scale level could be scalable and transferrable to create the spatial functions to activity relationship of spaces to the built and human environment.

Computations spatial patterns have been applied before, to form understanding of the 'behaviour of Pharaoh's ant colonies where the interest was to model individual ants in such a way that the whole system will show a reliable self-organisation and exhibit emergent behaviour' (Gheorghe, 2004). This research has progressed further through self-assembled 3D nanostuctures where the spatial arrangements were formed by carving and creating the forms from solid

Figure 5. Reaction circuits (taken from Chandran et al., 2011).

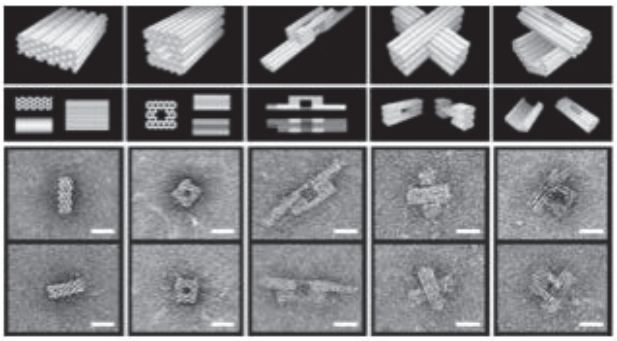

Figure 6. Nanostructures (taken from Cadnano, 2011).

3D honeycomb-like structures. This was achieved by design automation software (Cadnano, 2011) (Figure 6).

This approach to form complex spatial formation of these 'networks provide a powerful means of expressing patterns that can be self-organised. They can capture simple patterns that are directly expressed in terms of local interactions, and they can be combined to form more complex pattern networks' (Coore, 2004). This evolution in the creation of nanostructures by self-assembly principles to form materials and objects, could, as Reif et al. (2005) expressed, be a basis for potential large scale demonstrations.

Objective:

- 2. To use encoded values inputs (Figure 3) to extract optimised values for experimental spatial conditions, configurations and constraints upon relationship to form new emergent spatial formations, by application of biomolecular self-assembly computation.

7. Conclusion

Could there be evolution of our understanding of space by the integration of two seemingly contrasting worlds of culture and defined fixed spaces. To facilitate an embryological approach to combine the two spatial systems as a singularity, to determine output values. To use these encoded values as inputs to create generative space forming, using biomolecular computation. This computation could enable spatial arrangements being generated by a collection of voids enclosed by surface, that contain the encoded spatial value functions in determining the spatial surfaces around them. This self-assembled 3D spatial system could be formed by carving and creating the spatial voids from solid 3D structures to create spatial geometries.

References

Alexander, C.: 1964, *Notes on the Synthesis of Form*, Harvard University.
Cadnano: 2011, "cadnano". Available from Open Source Repository <http://www.cadnano.org/> (accessed 2011).
Chandran, H., Gopalkrishnan, N., Phillips, A. and Reif, J.: 2011, Localized Hybridization Circuits, *DNA'11 Proceedings of the 17th international conference on DNA computing and molecular programming*, Springer, Berlin, 64–83.
Cobo, M. J., Lopez-Herrera, A. G., Herrera-Viedma, E. and Herrera, F.: 2011, Science Mapping Software Tools: Review, Analysis, and Cooperative Study Among Tools, *Journal of the American Society for information science and technology*, **62**(7), 1382–1402.
Coore, D.: 2004, Towards a Universal Language for Amorphous Computing, *International Conference on Complex systems – ICCS2004*.
DfEE: 1999, *The Education (School Premises) Regulations 1999*, The Stationary Office, London.
Eastman, C. M. and Henrion, M.: 1978, Graphical Language for Interactive Design – GLIDE, Research report 76, Institute of Physical Planning, Carnegie Mellon University, Pittsburgh, PA.
Erikson, R. and Markuson, C. B.: 2007, *Designing a School Library Media Centre for the future*, American Library Association, Chicago.
Fairweather, L.: 2008, *A J Metric Handbook*, Architectural Press, London.
Gheorghe, M.: 2004, P-System: A Modeling Language, Department of Computer Science, Sheffield University.
Hall, E. T.: 1966, *The Hidden Dimension*, Anchor Books, New York.
Hall, E. T.: 1976, *Beyond Culture*, Anchor Books, New York.
Hensel, M. and Menges, A.: 2006, *Morpho-Ecologies*, Architectural Association, London.
Kwinters, S.: 2002, *Architecture of Time: Towards a Theory of the Event in Modernist Culture*, MIT, Boston.
Lawson, B.: 2006, *How Designers Think*, Biddles, Norfolk.
Lovelock, J.: 1991, *Healing Gaia – Practical Medicine for the Planet*, Harmony Books, New York.
Zaera-Polo, A., Moussavi, F., Kwinter, S., de Landa, M., Cache, B. and Wigley, M.: 2004, *Phylogenesis: foa's ark*, Actar, Barcelona.
Qian, L. and Winfree, E.: 2011, Scaling up Digital Circuit Computation with DNA Strand Displacement Cascade, *Science*, **332**(6034), 1196–1201.
Reif, J. H., LaBean, T. H., Sahu, S., Yan, H. and Yin, P.: 2005, Design, Simulation, and Experimental Demonstration of Self-assembled DNA Nanostructures and Motors, *Lecture Notes for Computer Science (LNCS)*, **3566**, 173–187.
Reiser, J. and Umemoto, N.: 2006, *Atlas of Novel Tectonics*, Princeton Architectural, New York.
Terzidis, K.: 2006, *Algorithmic Architecture*, Elsevier, Oxford.

OPEN SYSTEMS IN PRACTICE

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PERFORMANCE-BASED DESIGN

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Abstract. Building Information Modeling (BIM) and building performance simulation present opportunities to radically change the architectural design process, which has similarly radical implications upon the design collaboration process. The new technologies and processes create opportunities to meet and surpass the traditional architectural knowledge base that forms the basis for the design process. Outlined in this presentation are the results of a case study that employed BIM technology and performance simulation tools within the context of real project delivery.

Keywords. Mass customization; simulation; daylight analysis; conceptual energy model.

1. Introduction

Building performance has long been recognized as an important issue in architectural design, and has long been considered a seminal component in the value-system of architectural design. Performance-based design may be generally considered as an approach in which building performance becomes the guiding factors in design.

Advanced approaches to performance-based design are fundamentally different from conventional CAD (Computer Aided Design) simulation processes. Traditional simulation tools are premised upon the ability to simulate and evaluate performance of the object itself once it has been defined at an appropriate and desired level of resolution. Thus they are rarely employed in early conceptual stages of design. Current technologies are, to certain extent, capable of the integration of design synthesis formation processes that are directly informed by performance-based simulations.

Conventionally, engineers typically size building systems to meet the demands created by program, use and aesthetic desire. Architects have become addicted to what engineers can do for us. A deliberately multidisciplinary approach to building performance – including energy performance – coordinated and managed by the architect, should be embedded into every project team's workflow.

Performance-based design is redefined as the ability to directly manipulate the geometric properties of a digital model on the basis of performative analyses in order to optimize performance. Instead of analyzing the performance of a design, and modifying it accordingly, ultimately it may be possible to directly inform, generate and modify the design model using performance-based simulations. This performance-based design approach engages energy modeling directly with design generation, thus informing major design decisions and providing continuous feedback.

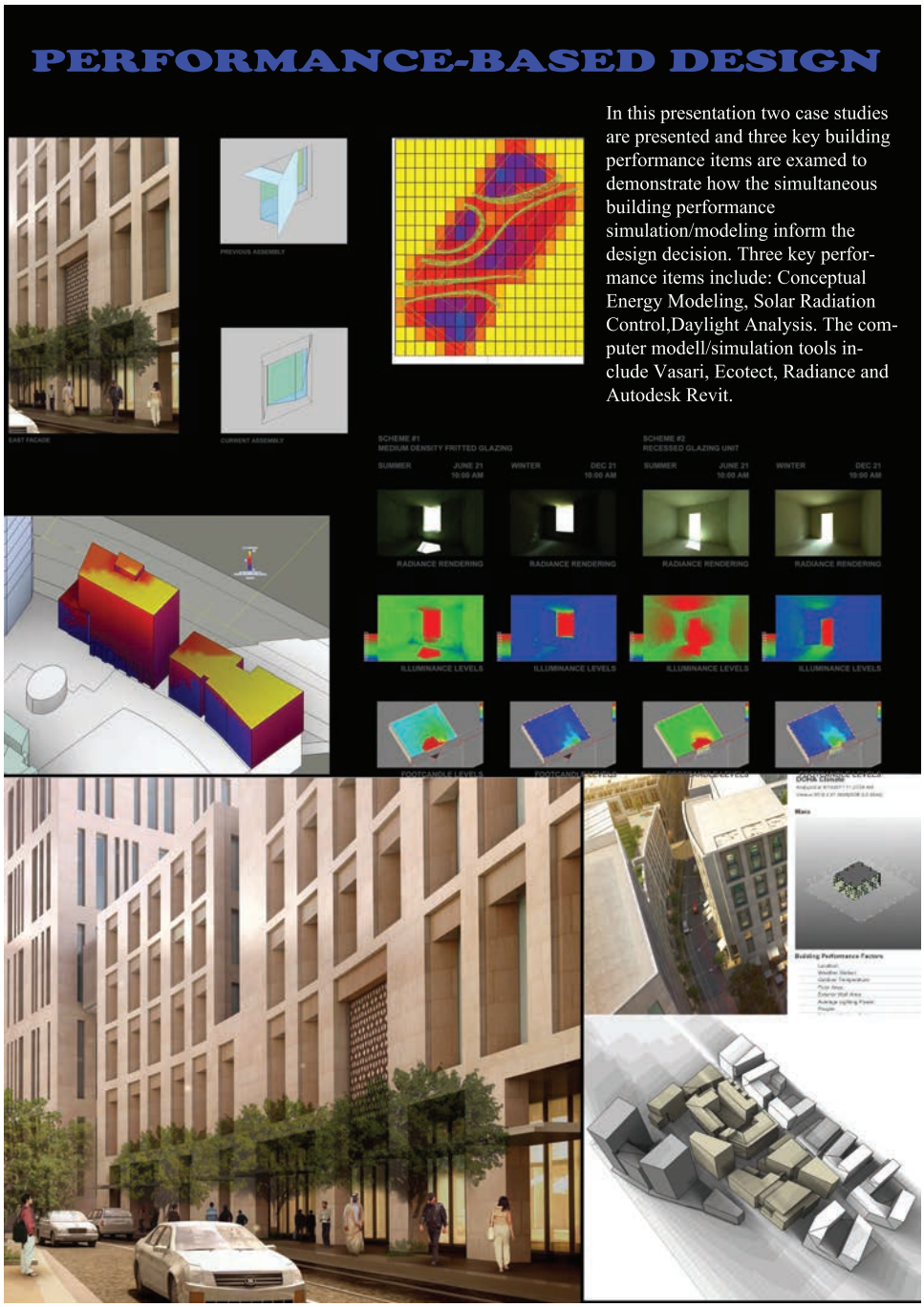
In the following section a case study is presented and three key building performance aspects are examined to demonstrate how the simultaneous building performance simulation/modeling inform the design decision. The three key performance aspects are: conceptual energy modeling, solar radiation control, and daylight analysis. The computer simulation tools used include Vasari, Ecotect, Radiance and Revit.

2. MHOD (Msherireb Heart Of Doha) – Form Optimization, Soar Radiation

The design process of MHOD is an typical case study of a performance-based approach including parametric design controlled by an interactive process towards optimization of performance, in this case, the building geometry and the skin were modified according to energy model performance and solar radiation intensity. Before starting the design, the architects first used the Ecotect weather tool to study the local climate and environment.

After having a thorough understanding of the local climate, multiple design options have been developed in Revit Architecture and brought into Vasari for conceptual energy model simulation. Once a building form has been selected for further development, the next step is to develop the building envelope and architectural language. In this step, the architect used Vasari to manipulate the quantity and characteristics of architectural components; glazing reflectance, shading strategy, and insulation based on solar radiation simulation result. This interactive design process has opened up a universe of possibilities. The static coordinates of shapes and forms of conventional digital media are replaced by computationally dynamic transformability controls perturbations that generate discrete building façade variations within design formation processes. The building components such as glazing and shading devices are no longer an addition to the building envelope, instead, the object is generated by simulating its performance.

A important goal in this project is to introduce sufficient daylight while limiting the glazing-wall ration to less than twenty file percent. During the design process, Ecotect has been employed to study the daylight intensity in relationship to the optimized window configuration.


PERFORMANCE-BASED DESIGN
In this presentation two case studies are presented and three key building performance items are examed to demonstrate how the simultaneous building performance simulation/modeling inform the design decision. Three key performance items include: Conceptual Energy Modeling, Solar Radiation Control,Daylight Analysis. The computer modell/simulation tools include Vasari, Ecotect, Radiance and Autodesk Revit.
EAST FACADE
PREVIOUS ASSEMBLY
CURRENT ASSEMBLY
SCHEME #1
MEDIUM DENSITY FRITTED GLAZING
SCHEME #2
RECESSED GLAZING UNIT
SUMMER
JUNE 21
10:00 AM
WINTER
DEC 21
10:00 AM
RADIANCE RENDERING
ILLUMINANCE LEVELS
Building Performance Factors

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THE WORLD WITHIN

A home cinema

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Abstract. 'The World Within' is an intimate family space, in an existing residence of goldsmith located in Ahmedabad, India. A jeweller understood and appreciated the intricacy of design as well as delicacy of workmanship in his profession, hence in architecture. Therefore, the idea of making an elegant crystal using principle of cracking is proposed to generate numerous unique facets. In order to create a unique experience different from the rest of the house outside this room, a continuous inner envelope is made. Variation of same design in 2D and 3D are used to dissolve the edges of floor, walls and ceiling. Lights are integrated by choosing specific facets forming a gradient of intensity flowing away from the screen. Voids are created within the facets to place various equipments. Design generation, iteration and integration are done through Grasshopper script. Fabrication followed standard process of cutting and numbering each piece with a CNC router. Assembly on site, done by local carpenters, remained the most challenging as well as interesting aspect of the project.

Keywords. Recursion; home cinema; generative design.

1. Introduction

The project brief was to make a home cinema that explore and experiment unconventional ideas with new technology. Proposed space for this was a covered balcony (veranda), 6.25 m x 3.5 m, on the first floor in an existing bungalow. Due to small volume and use of sound absorbing materials, in-depth acoustical analysis was not a serious consideration.

2. Design Generation

Space was fragmented. North side was full window facing the street, South a blank wall, East side had a bay window with a seat built in where as from the West side one entered the space which varied in wall thickness creating a niche. Flooring was disjointed with required slope to drain water and had a stepped ceiling. Smaller gestures of adding element of interest were adding to the fragments. In order to give a unique environment, decision was made to create a continuous inner envelope that unifies five surfaces.

Generative design and digital fabrication in architecture are relatively recent and rare in India. Therefore, the choice of using 'planer facets' was made, especially for fabrication and assembly ease. Simultaneously various logics to create faceted surfaces were referred, of which, the concept of cracking, was best suitable. Same logic has been observed in the physical formation of diamonds associating to the owner's profession.

Combining two logics, envelope and facets, a continuous inner envelope was lined with larger triangular surfaces where South wall was identified for projection, ceiling gently sloping from high to low negotiating existing stepped ceiling and opened up in the North with full length window. Algorithm is applied on triangular base surfaces, which is written in Grasshopper to create facets. It followed simple steps: find the centroid of each large triangular surface; draw lines joining centroid to the vertices forming 3 smaller triangles recursively. Recursion was limited by density parameter coupled with special requirements to generate corresponding patterns. This resulted variation such as the ceiling took density gradients from low to high in South to North direction, high density cloud was generated in the niche for mural (West wall), fairly distributed in the East wall taking care of the bay window, where as projection wall was least dense. 2D was then translated to 3D by lifting up centroid perpendicular to respective flat surface responding the room size and clear height within a range of 50 – 150mm on wall and 0 – 600 mm in the ceiling resulting a homogeneous heterogeneity.

Lights were integrated by choosing specific facets following intensity gradient creating of a flow away from the screen. Mural had special light embedded. Voids were created within the facets to place various equipments like split air condition, projector, speakers, etc. Reflected ceiling pattern in 2D was used to weave a custom made carpet for the room adding to the continuity of design. Similarly curtains were designed to be embroidered or painted. Due to time constrains this is not realised. Concept was carried forward till furniture design to house equipments like DVD player, X-box, music system, etc. Seating arrangement and soft furnishing was out of scope of the project.

3. Fabrication and Assembly Challenges

Design was a prototyped at scale1:20 to understand fabrication logic using laser cutting and paper foldouts. This also gave a clearer picture of the proposed design and construction logic to the client. 8mm medium density fibreboard was used for the panels and 19mm plywood formed the substructure. Actual fabrication followed standard process of cutting, engraving and numbering each piece with a CNC router using foldout templates. First batch of cut pieces were brought into workshop, for assembly and then to be installed on site. But due to the lack of experience on the part of workmanship in given method it did not work out.

From this point onwards customisation on processes based on available tools and skill set began. Traditionally in India, carpenters are used to work on site. Therefore, the plan had to be modified and entire assembly took place on site. Another fact discovered that carpenters were accustom to read three-dimensional geometry as the scaled prototype did not help them understanding construction logic. Therefore, entire design had to be converted to 2D drawings (sections and elevations) with basic dimensions including each perpendicular dimension of lifted centroid from its flat plane. The carpenters precisely chamfered each piece connecting to the next. This is only possible because of their skill set, experience, cooperation and urge to create something new.

Choice of finishes also went through various phases. Options to paint, acoustic paint vs polish, choice of colour ranging from lighter tones to black. Assumption that lighter colours (white) may create interesting shadow patterns of the facets was one where as function of home cinema needed to black out the space was the other. Black colour has negativity attached in Indian society, so the choice of darker shade of blue is finally applied on panelled surfaces and the lighter shade of blue with darker tone of lines are woven in the carpet.

4. Conclusion

In present Indian context application of generative design and digital fabrication to realize such complex geometry will require customisation of the process in resolving unforeseen issues from traditional workmanship.

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Carpenters: Suthar Rakesh, Indoria Hameersingh (Ajay), Suthar Vipul, Suthar Naresh.

the world within
urvi sheth + arya architects

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ISOMORPHIC CITY: A CUSTOMIZABLE FUTURE SCENARIO

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Abstract. This project shows a future city design/research project for an existing city in the desert southwest of the United States of America. The project, Isomorphic City, set in the year 2087 develops a truly customizable and ever-adapting computational approach to the built environment. The project was shaped by environmental criteria and social media. Part of the challenge was to design digital methodologies that could simulate this scenario in as live a way as possible, incorporating real-time, live data into the equation. Form was the result of inputted parameters verses the making of form in an object-like fashion. Going from a rule based way of simulating the complex urban condition to a more human agent-based approach based on collective intelligence and social behaviour patterns.

Keywords. Collective intelligence; parametric urban design; e-topias; live data; programmable matter.

1. Background

Making our urban environments sustainable – environmentally and socially is a key design issue today. William Mitchell, in E-topia wrote that because of the digital revolution of bits traditional urban models were no longer valid. He defined the new urban condition as "lean, green cities that work smarter, not harder. Their basic design principles may be boiled down to five points: 1. Dematerialization, 2. Demobilization, 3. Mass customization, 4. Intelligent operation and 5. Soft transformation" (Mitchell, 2000). Our current urban conditions are obviously a long way from these principles.

The project, Isomorphic City, was an attempt to holistically incorporate Mitchell's design criteria into a proposal which would anticipate what the future may hold, while researching and testing the latest available digital methodologies that can aid in this simulation process. This project was originally part of an undergraduate options

architecture studio which had input from graduate planning students in a related geo-design seminar. The proposal developed beyond the studio as an independent research project to allow more time to create live interfaces and make the model 'work' as originally hypothesized. Live digital models can still be fairly complex and clunky because of the need to usually interface several platforms together. In this instance Rhino grasshopper was selected as the main design interface, in part because of its NURBS-based logic, but also because of all the plug-ins which are developing daily, allowing this interface to connect with others in live ways.

2. Project Description

Mitchell's design principles are very pertinent today as they recognize the huge change that digital technologies have had on society. Part of the challenge for *Isomorphic City* was balancing this desire for a dynamic model with the growth constraints of existing resources. Conventional land use is rigid and lacks the ability to adapt and transform in the way that Mitchell deemed necessary. In Isomorphic City the proposed relationship of physical and digital space allows for a dynamic environment that could adapt to meet the direct needs of the inhabitants, in real-time, during the course of each day. Many dynamic/responsive systems incorporate sensors and are generally fairly technically complex in order to make parts that can adapt and change. For this particular scenario, set fifty years in the future, Programmable matter was utilized as the building block for the community, (digitally) creating form-finding aggregation.

Programmable matter was coined by Toffoli and Margolus (1991). There has been extensive research in programmable matter in biological and physical realms (Griffith, 2004). In this scenario we are referring to one of the more advanced areas of research – that of claytronics – reconfigurable nano-scale robots, which have the ability to move around, change shape and color as needed. Although the project was theoretical in nature we wanted to explore the relationship of the digital to the physical. Connecting to a real environment, i.e. an existing city was crucial to the digital simulation process as we could be specific about a given set of environmental criteria and data.

The vision predicts that digital designers, programmers, developers, architects, and environmental experts would constitute the main demographical work force required to maintain the city. Programmable matter will become autonomous; creating itself, yet designers and programmers will be needed to shape the matter, generate spaces and manifest the visions of the city inhabitants, on a personal level. Waste, as a concept, was created by human beings. In this future scenario the thought and ideology of waste will be transformed. Resources, energy, and water use of the city inhabitants will be directly monitored and will limit potential

population growth within areas of the city. The hyper-advanced interface of programmable matter has the ability to reshape to accommodate water storage for future use, as well as generate power on every surface exposed to the sun with a skin of electrically super-conductive nano-graphene. Mitchell wrote that "If you want adaptability, responsive software beats reconfigurable hardware…it is no longer the architectural programmer who controls space use, and thereby expresses power; it is now the software programmer" (Mitchell, 2003).

In order to be socially sustainable it is necessary to incorporate input from individuals rather than rely on more rigid top down approaches. Shin et al (2011) have claimed that the incorporation of direct participation of citizens, in this project's case via social networking data, creates a shift from rule-based simulation to a human agent-based approach. One of the keys to a successful city is also a diversity of programs and people. The proximity of home, work, and communal space in Isomorphic City allows for this life, plus gives a reduction in commuting time. Traditional streets take up space and damage the environment. Roads within the Isomorphic City will recalibrate and manifest as they are needed, and their matter will be repurposed when not in use. The digital plaza, the socio-cultural centre of the city, allows for virtual and surrogate travel. This eliminates the need for long distance travel as local space is connected to long distance digital space – thus lowering the ecological footprint of residents.

References

Griffith, S.: 2004, Growing Machines, PhD Dissertation, Massachusetts Institute of Technology, Cambridge, MA.

Mitchell, W.: 2000, *E-topia: 'urban life Jim – but not as we know it'*, MIT, Cambridge, MA.

Mitchell, W.: 2003, *Me++: The Cyborg Self and the Networked City*, MIT, Cambridge, MA.

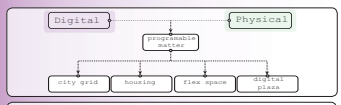
Shin, D., Muller, S. and Schmitt, G.: 2011, A Crowdsourcing Urban Simulation Platform Using Mobile Devices and Social Sensing, *CAAD Futures 2011*, Liege, Belgium, 233–246.

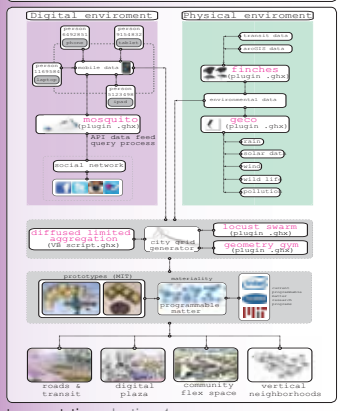
Toffoli, T. and Margolus, N.: 1991, Programmable matter: concepts and realization, *Physica D: Nonlinear Phenomena*, **47**, 263–272.

ISOMORPHIC CITY

a Customizable Future Scenario

A future city design/research project for an existing city in the desert southwest of the UnitedStates of America. The project, 'Isomorphic City,' set in the year 2087 develops a truly customizable and ever-adapting computational approach to the built environment which was shaped by environmental issues and social media. Part of the challenge was to design digital methodologies that could simulate this future scenario in as live a way as possible, incorporating real-time, live data into the equation. Form was the result of inputted parameters verses the making of form in an 'object-like' fashion. Going from a rule based way of simulating the complex urban condition to a more human agent-based approach based on collective intelligence and social behaviour patterns.





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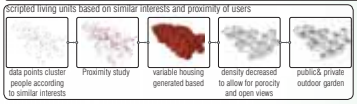
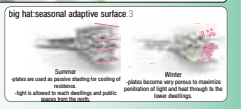
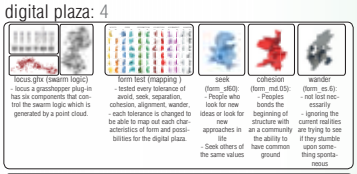




digital plaza: 4



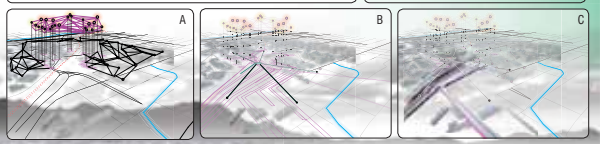
transportation:adaptive .1

Existing roads take up space, ruin the environment, and become very congested which wastes fossil fuels. Programmable matter roads are generated only when needed, and the PM is sent back to the system for reuse. The system can calculate the fastest possible route to your destination just like Google maps, and generate roads for you.

city grid:live adaptive

The development of the new city (isomorphic), The entire process is dictated by geo tag hot spots which show what spaces are in use and that information informs the cities development.

A. Hotspots of Tucson are selected through social media that are location based B. Then a new city grid is imposed over the hotspots which then go into flux with one another and change when hot spots shift over time C. The development of the "big hat" plates over the transportation lines is created which support housing units and flexible spaces with the digital plaza radiating out from the heart of the Isomorphic City.



R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 739–742. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

SYNTHETIC MANUFACTURING: RESILIENT MODULAR SYSTEMS (RMS)

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Abstract. Resilient Modular System (RMS) (temporal + structural) is a multi-disciplinary research proposal to forge the synergy and efforts between three different colleges/departments within the University of Houston: College of Architecture, Department of Industrial Engineering, and Department of Material Studies and Engineering, designed into a modular system that could be applied as urban interventions within the context of temporary and permanent settings. Using both eco-intelligent architectural design objectives, the knowledge and technique of manipulating sustainable materials ultimately pursues a positive impact on the planet as a growth opportunity engenders a focus on enhancing benefits (not only reducing costs) through its decision-making and actions – taking an approach of optimization rather than minimization. This project can understand the perspective of "people, planet and profit," as expansionist and enabling leadership through the achievement of advanced success metrics. For example, the concept of effective design of products and services should move beyond typical measures of quality – cost, performance and aesthetics – to integrate and apply additional objectives addressing the environment and social responsibility.

Keywords. Construction alternatives; waste management; offsite production; fabrication; form/fit/analysis; modularity.

The premise of the RMS (temporal + structural) project proposal is two-fold: A) to investigate the opportunities that allow for temporary and biodegradable structures, which could be utilized for temporary construction sites within the built environment, and B) to explore the structural significance and integrity of a modular structure utilising repurposed construction waste.

Most contractors are concerned about the cost of the labour that is needed to deconstruct materials for reuse or recycling. However, it has been shown that effective waste management during construction, renovation and demolition (CRD) projects not only help protect the environment, but can also generate

significant economic savings. Demonstration projects have shown that the diversion of waste from landfill can reduce waste disposal costs by up to 30%. This is accomplished through reduced tipping and haulage fees and the sale of reusable and recyclable materials.

The idea of the RMS (temporal) is the ability of it to become an ecological and resilient modular construct for the built environment that could be subsequently dissolved, yet, in an effort of full-cycle design, also contribute to nourishing the natural landscape.

The temporary proposal is that one of these structures could be possibly constructed as a retaining wall system – similar to the ones that are seen along the side of the highway or a landslide retention wall. The composite within the mixture of this will consist of ceramic filler, broken down glass, and biodegradable plastic as the main composite material. The process of this works as follows: 1) a landslide retaining wall is constructed with the RMS module; 2) due to exposure and UV tested breakdown, when the biodegradable plastic comes to the end-life; 3) the plastic will degrade and dissolve; 4) Since the plastic is made with a mixture of ceramic filler; 5) when the plastic dissolves; 6) the ceramic filler will be left, and since the ceramic filler itself retains moister; 7) when the ceramic filler is deposited into the soil, it would provide itself as a form of nourishment for plantation and development for agricultural growth.

The primary material research for the RMS (temporal), ephemeral structure, will be based on agricultural or soy-based biodegradable polymers have been in research since the late 90s and have been improved, bought out and carried forward, by some of the world's largest companies, like food and agricultural giant Cargill, who in 2008, spent over 22 million USD on developing a method to research and use polyols that can replace petroleum-based chemicals. The most effective method is to blend soy protein plastic with biodegradable polymer to form soy protein based biodegradable plastic, and forming the material with the method of extrusion and injection-molding to form useable pieces of plastic. Therefore, using the same traditional methods of constructing plastics, the same design fabricated parts would be used for applying similar 'thermoforming' or 'vacuum' forming techniques into constructing the prototypes.

While the secondary research for the RMS (structural) will be for repurposing construction waste, as a mixture for the remediation of the structural testing and joint detailing, the same modular structure will be utilized to further the innovate on studying the structural form/fix/analysis of the RMS (structural) modular.

Project managers and construction contractors have long recognized the importance of reducing waste and salvaging high value construction and demolition materials such as copper and other metals. Contractors are usually careful about the quantity of materials ordered, how materials are used and how to carefully

de-construct valuable materials. In most cases however, materials that are more difficult to separate and that are worth less per unit weight are still going to landfill, even when they are present in large quantities. This represents an inefficient use of natural resources and uses up landfill capacity unnecessarily.

Unfortunately, some contractors do not realize that there are new opportunities for waste minimization, while others are reluctant to implement environmental practices because they believe these practices will increase their project costs. Most contractors are concerned about the cost of the labor that is needed to deconstruct materials for reuse or recycling. However, it has been shown that effective waste management during construction, renovation and demolition (CRD) projects not only help protect the environment, but can also generate significant economic savings. Demonstration projects have shown that the diversion of waste from landfill can reduce waste disposal costs by up to 30%. This is accomplished through reduced tipping and haulage fees and the sale of reusable and recyclable materials.

The diversion of CRD waste from landfill sites is an issue that has been gaining attention within both the public and private sectors. Surveys have indicated that as much as one third of the 20 million tonnes of solid waste of municipal waste streams is generated by construction, renovation and demolition activities. Many of our landfill sites are reaching capacity. In addition, CRD waste is sometimes illegally dumped or burned, causing land, air and water pollution. The increasing costs of disposal are ultimately reflected in project costs, as contractors must incorporate anticipated disposal costs in their bid costing. Realities such as these emphasize the need for initiatives that focus on reducing and diverting as much waste as possible from CRD activities.

Incorporating the 3Rs (reduce, reuse and recycle) into construction, renovation and demolition waste management creates a closed-loop manufacturing and purchasing cycle. This significantly reduces the need to extract raw materials, reduces the amount of materials going to landfill sites and reduces the life-cycle costs of buildings and building materials.

Acknowledgements

RMS (temporal + structural) is a multi-disciplinary research proposal involving Prof Wendy W. Fok (Architecture/Design/Prototyping), a graduate student (Architecture/Design/Proto-typing), Prof Ali Kamrani (Patent/Industrial Engineering/Modular design aspects for form and fit analysis), and Prof Ramanan Krishnamoorti (Material Sciences/Bio-related engineering).

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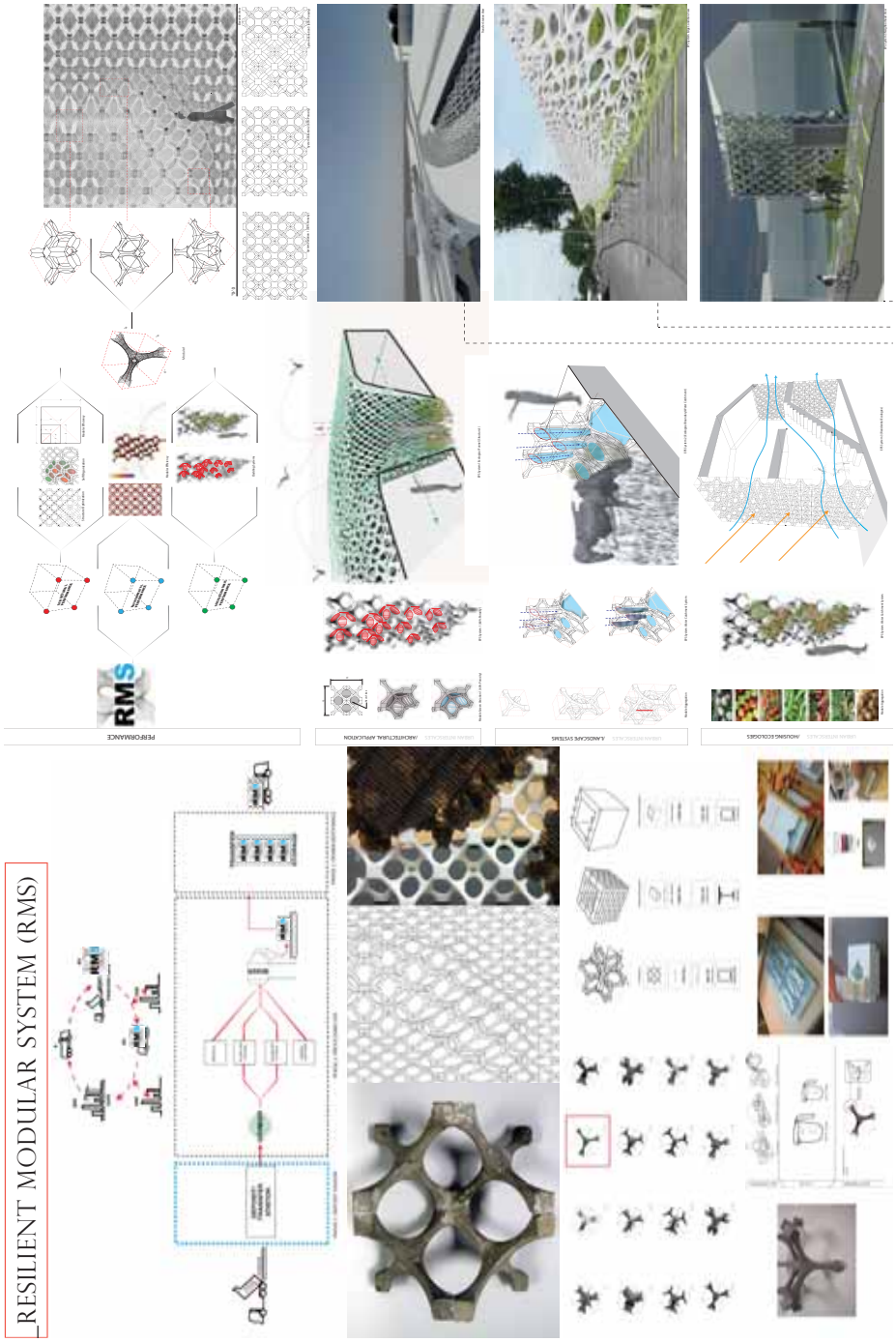
RESILIENT MODULAR SYSTEM (RMS)
RMS
PERFORMANCE
ARCHITECTURAL APPLICATION
LANDSCAPE SYSTEMS
HOUSING ECOLOGIES

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 743–745. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

INDUSTRY-WIDE ADOPTION THROUGH A COMPREHENSIVE BUILDING INFORMATION MODELLING (BIM) ROADMAP AND BIM ELECTRONIC REGULATORY SUBMISSION

Leadership of Singapore Government

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Abstract. Building Information Modelling (BIM) has been identified as one of the key technology drivers under the Singapore Construction Productivity & Capability Roadmap to spur the construction industry towards higher productivity and capability. The Singapore Building and Construction Authority (BCA) has formulated a comprehensive BIM Roadmap to steer the industry-wide adoption by 2015, through initiatives such as incentivising early adopters, public sector taking the lead, building BIM capability & capacity, facilitating the transition from 2D CAD to BIM, and regulatory approval.

Keywords. BIM; construction; Singapore; productivity; roadmap.

1. Introduction

Building Information Modelling (BIM) has been identified as one of the key technology drivers under the Singapore Construction Productivity & Capability Roadmap to spur the construction industry towards higher productivity and capability. The government's target is to make BIM mandatory for new public sector building projects in Singapore as early as 2012, and to achieve an 80% BIM adoption rate across the construction industry by 2015. With this target, the Singapore Building and Construction Authority (BCA) has formulated a comprehensive BIM Roadmap to steer the industry-wide adoption by 2015, through initiatives such as incentivising early adopters, public sector taking the lead, building BIM capability & capacity, facilitating the transition from 2D CAD to BIM, and regulatory approval (Figure 1). The adoption of BIM would lead to higher productivity gains

and lesser construction conflicts, as well as more sustainable building designs that allow quantification of "green" outcome directly from virtual building models.

The BIM Roadmap has indeed created a breakthrough for Singapore as we are so far the world first government who has been active with the various initiatives in propagating the BIM adoption nation-wide and with consolidated efforts to allow BIM electronic submission for multi-agencies' approval. The BIM Electronic Submission initiative was also reported by Autodesk as a world's first by a government authority, and BCA was conferred the BIM Recognition Award on 14 August 2009 for leadership, innovation and excellence in driving the transformation of building industry through BIM in Singapore.

Starting in year 2012, Singapore Government Procurement Entities (GPEs) have stipulated BIM as a technology to be used in new public sector building projects with estimated contract value larger than $10million. Since then, a number of key activities have been carried out to prepare both the local demand and the supply side. A BIM Steering Committee was also setup in July 2011 mainly to steer the implementation of the Roadmap, in particular, to spearhead the development of local BIM Standards and to address implementation issues that might impede the industry BIM adoption.

From the regulatory perspective, CORENET (COnstruction Real Estate NETwork) Electronic Submission System, which has successfully enabled entire construction industry to transform from manual to electronic submission since 2011, was the key to move the Singapore construction industry to next level of excellence by transiting from 2D CAD to 3D BIM technology. Together with the industry professionals, the CORENET participating agencies have worked creatively to come up with innovative ideas and solutions to help industry professionals to adopt the BIM technology with a minimal learning curve. Moving forward, the BIM electronic submission for regulatory approval through CORENET would be made mandatory starting with the architecture electronic submission in 2013.

Under its training framework, BCA has developed a series of locally customised progression training path to the existing practitioners, through its academy arm at BCA Academy. The framework also provides progression paths to allow BIM users to move from BIM modelling to management skills. Besides training the existing practitioners, BCA has also engaged the various Institutes of Higher Learning (IHLs) in Singapore to help them to incorporate BIM as part of their curriculum so that their students joining the construction industry are BIM ready.

Lastly, to encourage the industry to come on-board the BIM journey as early as possible, BCA had rolled out the BIM Fund under the Construction Productivity and Capability Fund (CPCF) since June 2010. The fund helps the local firms to defray their initial BIM investment costs on training, consultancy, manpower, software and hardware.

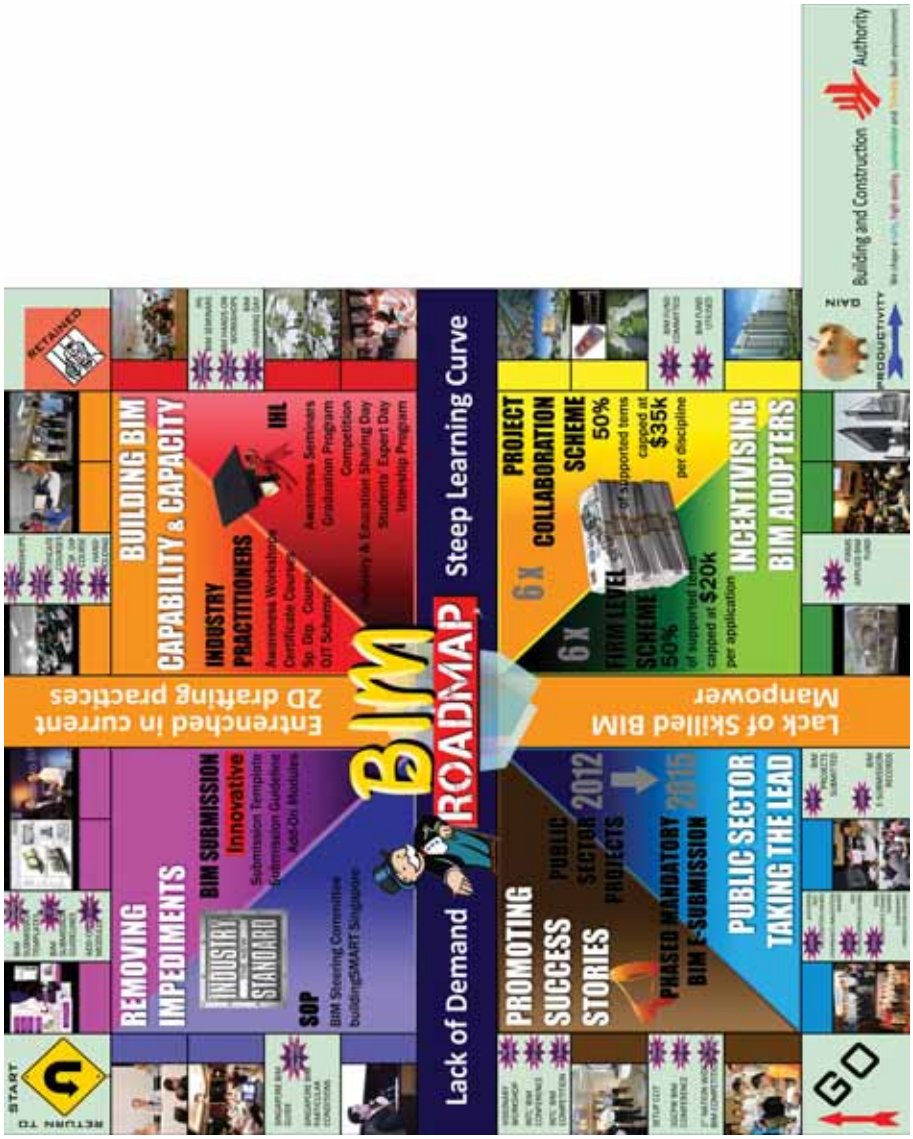

Figure 1. Graphical depiction of the Singapore Building Construction Authority BIM Roadmap.

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GENERATIVE BAMBOO HOUSE: N4+ GLUEBAM HOUSE/石榴居

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Abstract. "Glued bamboo prefabricated construction system" is developed by the Advanced Architecture Lab (AAL) together with the bamboo institute of the Chinese Academy of Forestry. The Glue-bam investigation is a three years long research project in Huazhong University of Science and Technology Advanced Architecture Lab sponsored by Advance Construction Information Development (ACID). Integrating computational design application with material to achieve DIY housing through parametric computational aid designing, brings designers closer to its client. The project aims to transform the rich bamboo resource in China into an industrialized building structure material. "Glued bamboo prefabricated construction system" advocates a social design, social produce solution and a customizable construction system upon prefabrication.

Keywords. Design-it yourself; glue laminated bamboo; generative construction.

1. Introduction

China, one of the fastest growing countries, faces fierce demand for mass public housing and emergency relieve housing. The energy waste, deforestation and material wastage in the construction industry place a big challenge in the future development of China cities. This unprecedented growth in demand call for the search for a fast, sustainable, reliable and mass customizable housing made readily available to the access of the masses.

With variations of contexts, climates and locations, the generative bamboo house need to reach a set of solutions (fabrication data) that is task-specific and geological specific reacting to the users' primary inputs and needs.

This research combines a bamboo material research with digital research in generative approaches in the design of bamboo-housing typologies. To facilitate a "design-it-yourself" design to construction process that is fully automated, providing a sustainable, versatile, and rapid instant housing typology for the general masses.

2. On Bamboo

As one of the fastest-growing plant on Earth, Bamboo is a vernacular material commonly used by the Chinese. Notable for its economic and cultural significance, bamboo could be groomed in various climatic conditions, providing a versatile, reliable, sustainable raw material as a building product. Our research partners, the bamboo institute of the Chinese Academy of Forestry, specialize in glued bamboo board concluded that the material embedded energy is 2300MJ lower and carbon dioxide is 370kg lower per meter square than typical reinforced concrete system. Through a systematic treatment of airing, hot/cold pressing, heating and high pressure gluing, the bamboo board is structurally stable, passing the JAS (日本农林标准).

3. The Generative Bamboo House

Understanding the different needs and considerations of the context, constrains and functions guides us to create specific typology for the generative bamboo housing. The Bamboo Single House for the rich, Incremental Bamboo House for the extension of row houses, Emergency Bamboo House for emergency needs, High Density Bamboo House for alternative addition for high density cities like Hong Kong are four housing typologies AAL identify and aims to tackle.

Simplicity and convenience is given a high priority for the programming of the generative bamboo house. The app (on i-pad) is perceived to be a simple drawing program that can be generated into fabrication data which can be ordered through online platform.

For our first prototype, the single housing typology, the user input is two basic polyline, one is the profile section of the house and the other is a plan curve of the fringe of the building. The programming background would optimize structural requirement, number and location of screws, distance and location of frame members, component and mass-fabrication of similar components.

4. First Prototype

Build mainly by student volunteers, the First Prototype of the generative bamboo house is completed in 25 days with simple tools like screws, hammer and drills. The material cost is significantly lower at approximately 100,000 RMB (not including labor cost). Some lessons we learn from this construction is the optimization in detailing, a more logical construction sequencing, linking parametric model with BIM to control on site construction, and possibility of pre-fabrication with laser cutting would fasten the process and lessen mistakes.

The First Prototype is a beta version of the single family houses; we plan to add more complexity like toilet, double flooring to push the typology more attractive for the general public.

5. IKEA-Able House

AAL (Advance Architecture Lab) pushes the boundary of computational in architecture through actual application of the tools we teaches in Huazhong University of Science and Technology. The Generative Bamboo House aims to materialize the idea of a "Design-it Yourself" Ikea-able house which a wide spectrum of people from governments, farmers, etc can design and build their own houses.

Acknowledgements

The authors would like to acknowledge Dr. Li Baofeng (Dean of Architecture, HUST), Mr Yu Hui (Private Sponsor), Zhou Chao (Chief Architect), Liu XiaoHu (Advisor) and all the student volunteers making this research possible.

References

Sass, L.: 2006, Instant House: Design and digital fabrication of housing for developing environments, *CAADRIA 2006: proceedings of the 11th International Conference on Computer Aided Architectural Design Research in Asia*, Kumamoto, Japan, 209–216.

Yueng, W. and Harkins J.: 2010, Digital Architecture For Humanitarian Design, *CAADRIA 2010: proceedings of the 15th International Conference on Computer Aided Architectural Design Research in Asia*, Hong Kong, China, 413–422.

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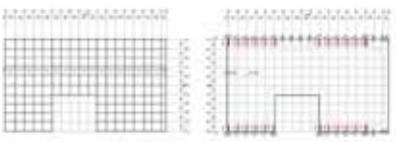
N4+ Gluebam House / Advanced Architecture Lab



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GOLDEN MOON

Hong Kong 2012 Mid-Autumn Festival Lantern Wonderland

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Abstract. The Golden Moon is a temporary architectural structure that explores how Hong Kong's unique building traditions and craftsmanship can be combined with contemporary design techniques in the creation of a highly expressive and captivating popular public event space. It is the 2012 Gold Award winning entry for the Lantern Wonderland design competition organised for the Mid-Autumn Festival and was on display for 6 days in Hong Kong's Victoria Park in the fall of 2012.

Keywords. Traditional craft; procedural modelling; bamboo; pavilion; Hong Kong.

1. Concept

The Mid-Autumn Festival is one of Hong Kong's most significant public holidays and has always drawn major popular attention for being a moment where family reunion is celebrated. The Golden Moon installation was planned as the highlight of this festival. Therefore its design revisits the concept of a Chinese lantern and makes a direct link to the legend of Chang'e, the Moon Goddess of Immortality – two elements strongly associated with the festival. According to the romantic story Chang'e lives on the moon, away from her husband Houyi who lives on earth. The couple can only meet on the night of the Mid-Autumn Festival when the moon is at its fullest and most beautiful. To graphically visualise the passionate love burning between the reunited couple that day, a 6-storey-high spherical lantern, symbolising the moon, is clad with abstracted flames in fiery colours and patterns and animated with a fiery light show. The lantern is placed in a reflection pool and is made large enough for up to 150 people to enter and be fully immersed in the sound and light experience.

2. Materials

For the construction of the Golden Moon traditional materials for making lanterns, such as translucent fabric, metal wire and bamboo, were translated to a large scale. A light-weight steel geodesic dome forms the pavilion's primary structure and is the basis for a computer-generated grid wrapped around it. This grid is materialised through a secondary structure from bamboo. For this, Hong Kong's traditional bamboo scaffolding techniques were used. This highly intuitive and imprecise craft was merged with exact digital design technology to accurately install and bend 2km of bamboo sticks into a grid wrapping the steel dome. This grid was then clad with stretch fabric flames, all lit up by animated LED lights.

3. Geometry & Colouration

The bamboo and flames follow a pattern based on an algorithm for sphere panellisation that produces purity and repetition around the equator and imperfection and approximation at the poles. This gradual change creates a dynamic space that draws a spectator's view up towards the tip. By putting the axis of this cladding grid not vertical but under an angle, the dome gets an asymmetric directionality. This motion is reinforced by the entrance which is placed along this tilted axis to draw people into the sphere where they get swept away along the grid's tangents and vectors. The colouration of the pavilion amplifies this effect: on top of the black painted steel structure eight different saturated colours of stretch fabric are used for the flames. The colours gradually range from ivory and yellow to intense orange, red and deep Bordeaux. The brightest colours are used at the tilted base whereas the darkest colours are used at the pole where they, together with the more scrambled geometry, make the pattern disintegrate into the black night sky.

4. "Building Simplexity"

The Golden Moon strategically combines digital design & fabrication techniques with traditional crafts and basic materials. Procedural modelling techniques were used to control the geometry: a sphere is wrapped with a diagrid according to a Fibonacci sequence that produces order along the equator and randomness at the poles. Code was used for the production of simple drawings that would allow the labour force to mark up intersections between the steel structure and bamboo easily. These drawings took traditional bamboo scaffolding construction detailing into consideration in the definition of installation tolerances (of around 10cm). Optimisation scripts were finally used to reduce the amount of unique stretch-fabric flames from 470 different units to 10 different types which could stretch and

adapt to their various conditions. All details and construction procedures were devised to allow for a high-speed production as only 11 days of onsite construction were available for this 6-storey-high pavilion. A very close conversation with the craftsmen was required from the beginning: preconceptions of building methods and familiar construction techniques had to be abandoned by all parties as both the digital and the material world demanded a new design and building set-up to be devised.

5. Conclusion

The Golden Moon was built in only 11 days and shows how complex geometry can be built at high speed and low cost with the simplest of means. It rethinks the premise of digital design by anchoring the paradigm in a strong materiality. With over 400,000 visitors during its 6-day lifespan, the pavilion design aimed for its dynamic space, structure, colour, texture and light to trigger a sensuous response from visitors of the 2012 Mid-Autumn Festival.

Acknowledgements

Competition Design | Kristof Crolla & Adam Fingrut of LEAD
Project Management | Laboratory for Explorative Architecture & Design Ltd.(LEAD), G/F 1 Tai On Terrace, Sheung Wan, Hong Kong S.A.R., www.l-e-a-d.pro
Project Management Team | Kristof Crolla, Sebastien Delagrange, Dannes Kok, Kenneth Cheung and Yi Sa Chan of LEAD, and Nicholas Benner, Chris Lee (Anthropods Associates Ltd.), Paulina Lau (APT Engineering Consultant Ltd.)
Construction | Free Form Construction Co. Ltd. (Main Contractor), Fonkwang Development Ltd. & Guangzhou Shipyard Company Ltd. (Steel), Wing Yick Scaffolders (Bamboo), Wings Design Production Ltd. (Fabric), LED Artist (LED)
Light & Sound Design | LED Artist
Photography | Kevin Ng, Grandy Lui and Pano Kalogeropoulos

Hong Kong 2012 Mid-Autumn Festival Lantern Wonderland

GOLDEN MOON

The Golden Moon is a temporary architectural structure that explores how Hong Kong's unique building traditions and craftsmanship can be combined with contemporary design techniques in the creation of a highly expressive and captivating popular public event space. It is the 2012 Gold Award winning entry for the Lantern Wonderland design competition organised for the Mid-Autumn Festival and was on display for 6 days in Hong Kong's Victoria Park in the fall of 2012. The Golden Moon was built in only 11 days and shows how complex geometry can be built at high speed and low cost with the simplest of means. It rethinks the premise of digital design by anchoring the paradigm in a strong materiality. With over 400,000 visitors during its 6-day lifespan, the pavilion design aimed for its dynamic space, structure, colour, texture and light to trigger a sensuous response from visitors of the 2012 Mid-Autumn Festival.

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BETWEEN THE OPEN AND CLOSED: A SIMPLE FACTORY BUILDING FOR THE TROPICS.

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Abstract. A Simple Factory Building for the Tropics is a built architectural example of the merging of passive design strategies, digital simulation and digital fabrication for a banal building typology. A series of simple yet important design approaches, sampled and transformed from regional historical precedents, allow for the emergence of passive architectural form while being linked to the realities of tempering air, minimizing solar load and digital construction technologies. Digital simulation and digital fabrication are used extensively in the testing and fabrication of the design solution. The result is an architecture located between the open and closed, durable and adaptable, digital and physical, passive and active. The design synthesis insures the project's relevance today and for its future life cycle both performatively and symbolically.

Keywords. Digital fabrication; simulation; performative envelopes; tropical architecture.

1. A Simple Factory Building

A Simple Factory Building was designed and built between 2009 to 2012 and located in the Upper Thompson region of Singapore. The architecture engages with the realities of both open and closed envelopes, passive and active technologies, digital simulation and fabrication, while finding means to encourage less energy consumption with passive modes of inhabitation, while imagining a durable and flexible architectural future. The design pre considers the complete life cycle; creating architecture that envisions its own destruction; a common occurrence in Singapore's recent history. This is a building that is approximately 98% recyclable.

As in many tropical architectural approaches, mitigation of solar gain is the main environmental driver. A double wall elevation system – a 1400mm *deep envelop* – combines passive strategies, durability, and digital fabrication while producing a dramatic expression for a banal building typology. The deep envelop operates as a lightweight brise soleil, recalling the shutters found in Straits shop-

house typologies and the Colonial "Black & White" bungalows of Singapore. The deep envelop is composed of two parts: a 400mm deep trellis fabricated in light-weight Dryvit (high density expanded polystyrene know as EIFS) that envelops the section continuously as a loop from the street, roof, car porch and rear facade of the building.[1] The open dryvit assembly weighs approximately 498kg/m3 compared to an equivalent masonry design of equivalent volume at 1750~2400kg/m3, a factor of four times lighter for an similar approach. A second layer of an aluminium awning window wall system, with Stopsol classic bronze glazing, provides the air tight seal for air conditioning and acoustic mitigation.

1.1. AN OBSCURING VEIL

The façade's trellis pattern operates as an obscuring veiling, limiting exteriors view in from the street. From street level, the resulting façade is an anamorphic pattern which creates an illusion of a taller building . Mies van der Rohe's emphasis on transparency – developed for a temperate environment – is inverted here; the design utilizes the veil as an apt metaphor for architecture of the tropics. Views from the interior out are carefully controlled, minimizing sightline to the traffic below – note the tighter dimension of the screen at the lower levels – while opening larger for more dramatic views to the landscape on the upper levels. Indeed, to veil is not to entirely conceal; rather the veil empowers the inhabitant behind the screen in a space of thermal comfort and optical privilege.

1.2. DIGITAL SIMULATION AND DIGITAL FABRICATION

The veil's profile is calibrated from 50mm at its exterior edge tapered to 80mm on its inward edge producing a thin exterior proportion while maximizing its ability to cut direct solar gain on its inner face. The horizontal members are tapered from 6 to 10 degrees off the horizon to shed rain, dirt, and sun. Finished in an off-white exterior stucco finish, the finish darkens with the accumulation of particulates from the industrial atmosphere; it is to appear weathered and aged.

The complex intersections of tapered horizontal and vertical members are possible through the deployment of modelling, simulation, and testing with Rhinoceros software. Digital models in Adobe Illustrator and Robert McNeel & Associates Rhinoceros 3D, tested in Autodesk's Ecotec are utilized to create the veil that is digitally precise, combining both Euclidean geometries and Boolean operations. Fabrication is produced through digital controlled hot wire cutting and CNC milling of solid polystyrene blocks.

The project represents a commitment to material research to utilize older materials and implement them in new and appropriate ways: in this case the EIFS

system is transformed from a temperate application often associated with cheap buildings to a tropical deployment symbolizing refinement and excellence. Digital fabrication merges with craftsmanship in a combination of the traditional and the technological; the results produce a design of elegant complexity as a resistance to the common and the expedient.

1.3. A PERFORMATIVE SURFACE

Individually each component – the trellis and the glazing window wall – contribute to achieving performance within Singapore's ETTV (Envelop Thermal Transfer Value) code controls (maximum permissible ETTV is at 50w/m2). The glazing and horizontal catwalk components (between the trellis and building proper) result in an ETTV calculation at 46.79 W/M2 – a factor suitable for submission and clearance purposes. The total ETTV calculation is estimated through Ecotect digital simulations at approximately 25.0 W/M2 when the Dryvit trellis assembly is accounted for. The façade design emerges as a solution that can accommodate multiple demands simultaneously; a tectonic surface that encapsulate the primary architectural mass, a envelop that calibrates views, limits solar heat gain, and conceals mechanical equipment. Through the deployment of a composition of a repeatable elements, albeit slightly changed along their position, the decorative surface merges with an atmospherically perfomative one, recalling the brise soleil of Le Corbusier in the Villa Shodhan in India, or his sun shade at the Carpenter Center for the Visual Arts at Harvard University. Closer to Singapore the façade alludes to the or the experiments of tropical buildings (recall James Ferrie and Partners' Wing On Life Building from 1975) yet made relevant to today through digital simulation and lightweight fabrication. Buckminster Fuller's question "How much does your building weigh?" sits as a driver for the façade's material formation. Open and closed, durable and adaptable, passive and active, the Simple Factory Building embodies simple but important architectural concepts for the production of relevant and model building for the tropics.

Endnotes

1. See product description: http://www.dryvit.com

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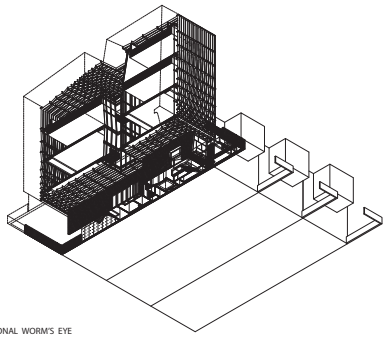
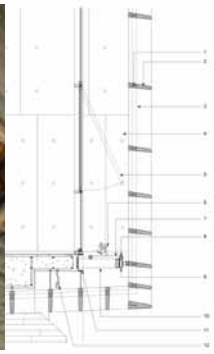
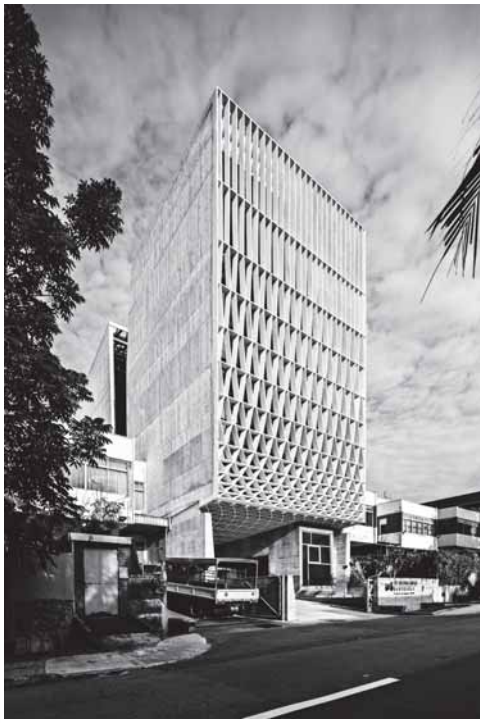
Project designed by Erik G. L'Heureux AIA LEED AP BD+C with Pencil Office; Architect of Record-Arya Architects; Structural Eng-HS Eng Consultants; MEP- K L Au & Associates.

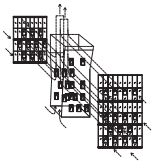


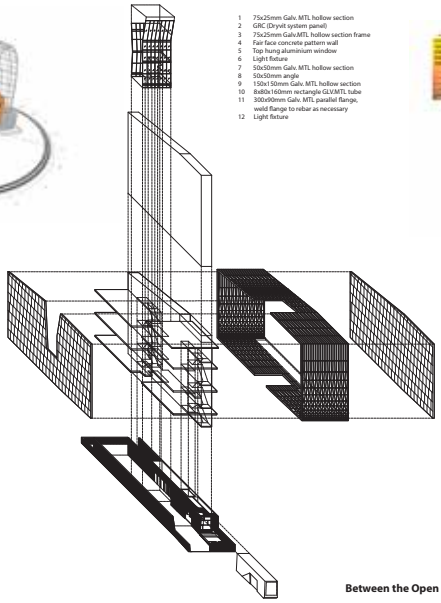
SECTIONAL WORM'S EYE



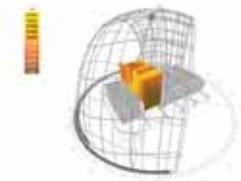


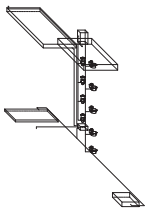
ECOTECT SUN PATH ANALYSIS





1 75x25mm Galv. MTL hollow section
2 GRC (Dryvit system panel)
3 75x25mm Galv.MTL hollow section frame
4 Fair face concrete pattern wall
5 Top hung aluminium window
6 Light fixture
7 50x50mm Galv. MTL hollow section
8 50x50mm angle
9 150x150mm Galv. MTL hollow section
10 8x80x160mm rectangle GLV.MTL tube
11 300x90mm Galv. MTL parallel flange, weld flange to rebar as necessary
12 Light fixture





ENVIRONMENTAL OBLIQUE

Erik G. L'HEUREUX, AIA LEED AP BD+C
Between the Open and Closed: A Simple Factory Build ing for the Tropics

SHAPE STUDIES

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 761–770. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

COMPUTER AIDED MODULAR GEOMETRIC MODELING, TO STUDY THE PERCEPTION OF SAFETY

Natural surveillance for perceived personal security

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Abstract. Natural surveillance is one key factor proposed, in the approach to decrease fear of crime. Building fenestrations and outdoor spaces like terrace, balconies and verandas that extend the interior spaces and the indoor activities, beyond the closed external shell of the buildings, are proposed by CPTED, in their place specific policy guidelines, to help design out fear and crime. In this background, this study on natural surveillance opportunities, explores typological variations of these component outdoor spaces of buildings, in line with variations in size and location. The affordances considered for this study specifically focus on the ways in which these spaces structure the visual fields for the external observer. This paper thus reports the survey of visual preferences exploring the spatial affordances of building spaces and their association with fear of crime.

Keywords. Natural surveillance; typology; fear of crime; visibility analysis.

1. Introduction

Crime is the result of a complex interaction between economic, social and cultural factors, including the physical environment that houses them. Fear of crime is the fear that crime educes and stimulates. Studies have been made in the area of 'Fear of crime' for several decades and it still attracts interest from social, economic, political and research perspectives.

Crime triangle theory puts the physical location (opportunity) as one of the three major factors that determine the type of crime or the behaviour of the criminals. Though for a fact we know that building don't commit crime, studies show that various features of the physical environment contribute to fear of crime. The built environment creates prospect, refuge, gives a feeling of entrapment or concealment,

sets the zone of proximies, enhances belongingness through feeling of territoriality and thus create sense of comfort, safety and security.

The relationship between the physical properties of the built space and the spatial experience it creates, in this case the perception of safety and security, needs generic descriptors of space like geometry, scale, orientation, alignment, etc to facilitate better understanding. These dimensions will help analyse the connection between the architecture of the physical environments and the user behaviour, to obtain biologically and psychologically relevant properties of the built environment. Crime prevention through environmental design (CPTED) recommends location specific policies as guidelines to architects, designers and planners, regarding the layout and design aspects of the component spaces of buildings. But architects with several other dimensions and higher objectives to satisfy, prioritize building fenestrations and outdoor spaces for their lighting and ventilation and scarcely for the surveillance offered.

Thus this study attempts to test several variations of building outdoor spaces, through visibility analysis and visual preference survey, to determine the degree of impact these component outdoor spaces of buildings have on fear of crime.

2. Review of Literature

The perceptions of personal security control the preferences of a user on places and spaces being used because the spatial properties of the built environment influence the subjective experiences of users. Even the building's exterior, though a mere packaging has close encounters with people and thereby influence their perception of these spaces (Gehl et al., 2006). In Fear of crime studies, emphasis on spatial characteristics are recorded since 1920s and 1930s, in the ecological studies of the Chicago school. Several theories, even from environmental psychology, explain human behaviour and experience by their interdependency with the environment. The evolutionary based theories of environmental preferences suggest that certain spatial settings were advantageous for the survival of a species and therefore corresponding preferences enhanced its fitness. Moffat (1983) proposed six broad categories to first generation place based crime prevention studies; Territoriality, access control, surveillance, target hardening, image/maintenance and active support (Geason et al., 1989). Among these broad areas of concern, surveillance is one key factor in the approach to decrease fear of crime.

2.1. NATURAL SURVEILLANCE

Natural Surveillance is the concept referring to the arrangement of physical design features, the activities and people, in order, to maximize opportunities for surveillance at the right moment in time and space, ultimately preventing crime (Cozens, 2002).

The primary focus of any surveillance strategy is to keep the intruders under observation and the undesirable behaviour under control (Sorensen et al., 2008). Jane Jacobs (1961), in 'The Death and Life of Great American cities' suggested that the eyes of local guardians must be scanning the built environment all the time for its design to be safe and successful. Oscar Newman's (1973) defensible space talks of natural surveillance in addition to territoriality, images and milieu. Crowe (2000) reinforces the importance of natural surveillance alongside maintenance, natural access, control and territorial reinforcement in CPTED design suggestions.

Features of the physical environment play a major role in providing natural surveillance. Natural surveillance of urban places is provided by occupants of the neighbouring buildings and the public on streets (Desyllas et al., 2003). The offenders look for desolated places to avoid being identified or caught while committing a crime. Enhanced surveillance will increase the vulnerability of the offenders. Hence, promoting natural surveillance will increase the risks of offending. Moreover due to the confidence of guardian interference, people feel more secure in areas with high surveillance.

Defensible space theory, situational crime prevention, secured by design (SBD) and CPTED and several place based crime prevention theories intend to promote natural surveillance to alleviate incidence and thus fear of crime'. Natural surveillance provided by building occupants, enhances the perception of personal security of people navigating through a built environment. Thoughtfully designed buildings and planned streets have great potential to increase natural surveillance and thus the feelings of security of the users. The number of unobstructed openings, type of building outdoor spaces and type of activity housed in that space aid people estimate the surveillance offered by the guardians. Both enhanced visibility and increased usage may enhance possibilities for natural surveillance (Welsh, 2009).

3. Purpose of the Study

Empirical research studying the impact of component parts of the built environment while evaluating its effectiveness of interventions in fear of crime is fraught with difficulty (Cozens et al., 2005). Designing by way of understanding typologies have been part of architecture for long and it helps classify and put several alternatives into groups, based on their similarities, as well as, to make distinctions between them (Guney, 2007). This study, with the aid of computer generated block variations will extend the use of typological studies for evaluating visual preferences of buildings, based on the perception of safety. The objective of this experiment is to evaluate the affordances of typological variations in building outdoor spaces, relative to its size and position, towards natural or informal surveillance and thus its impact on fear of crime.

4. Experiment

4.1. OBJECTIVE

Interrelations between spatial variations in buildings and visual preference were tested with this experiment. The visual preference and user's behavioural response were obtained for hypothetical block models, generated for this purpose. It was hypothesized that these different models of systematically represented variations will influence participant's visual preference.

In accordance with the overall objective of investigation, the visual preferences obtained via the survey were compared with the visual fields offered by the building through basic isovist calculation.

4.2. EXPERIMENTAL SETUP

Photo simulated models combine flexibility, controlled laboratory conditions, and a good degree of perceptual realism for even the hypothetical buildings. It allows systematic variation of spatial properties of the experimental environments. Thus this study used the basic 3D solid modelling technique of subtractive modelling, to model several variations of recessed outdoor spaces in a two story building, to study the aspect of surveillance towards reduction of fear of crime. The 3D models were created using AutoCAD 2013 and rendered using Autodesk 3ds Max Design 2013. In order to compare these buildings, the variations were normalized according to the range of visibility affordances.

4.3. METHOD

27 Elementary cubes (measuring 3 meters each side) were used to generate a modular geometric system of a block cube (9m x 9m x 9m). Subtractive modelling techniques transform this block cube into several morphological variations. No more than three blocks were removed at a time. Blocks which are not visible from the streets when removed were also left untouched. The ratio between block volume and openness and the isovist surface area calculations helped reduce the number of variations to eighteen options (Figure 1).

All visible side of the elementary cubes were given a door or a window. Each elementary block, when removed, to form an outdoor space, was marked with a 0.6m tall solid parapet wall. Positioning or location of the outdoor spaces and the size were varied in each study model. The resulting variations of the building outdoor spaces were surveyed to obtain the visual preferences of the observers.

Since the study used visibility analysis to verify the results, only one public street was located, 6m in front of the building. The entry to the building block was

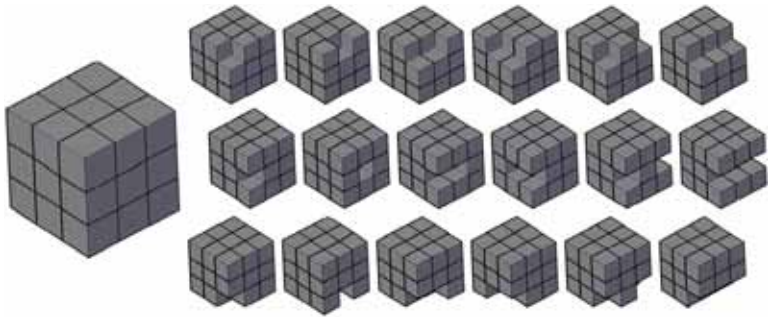

Figure 1. Generation of shapes based on 27 cubical elements – transforming to the 18 shapes taken for the study.

oriented to the streets making the building have direct access from the street. There were clear lines of sight between entrance foyer and street. Preset observation points and a block cube of similar dimension on either side of the generated model, with a side setback of 4m, determine the frame limits of the rendered output and also allow the consideration of field of view.

4.4. DATA

The data collected recorded the visual preferences of the participants for the eighteen options grouped under three categories. Three images from three different viewpoints were projected on screen for each option. Images from three viewpoints were to give a 180 degree view around the building to aid participants picture the building block without difficulty. Participants after viewing the images responded to them by answering the questionnaire survey.

4.5. CALCULATIONS

Isovists are viewshed polygons capturing the spatial properties of the built environment by describing the visible area from the user-centred perspective (Benedict, 1979). Thus isovist calculations were included as supplementary additions to help with analysis and study. The visible fields for the same block will vary as a user navigates along it. Hence the method of averaging isovist measurands for the same building from three different points rendered global characteristic values. The horizontal floor area as well as the vertical surface area of the outdoor space, visible to a human eye was calculated. The analysis then tested for interrelations between characteristic values derived from the isovist study and the behavioural data (Figure 2).

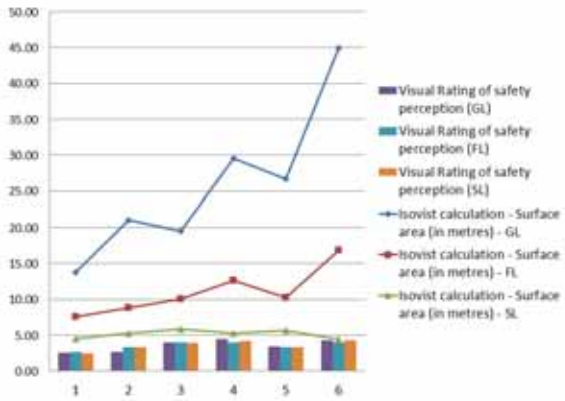

Figure 2. Isovist calculation (Visible surface area) plotted against the safety and security preference rating.

4.6. PARTICIPANTS

30 participants (12 female, 17 male) voluntarily participated in the experiment. Participants were all undergraduate university students of the department of architecture.

4.7. ANALYSIS AND RESULT

The questionnaire collected data on the participant's actual perception of fear of street crime, in the real world. It was observed that 76% of participants feared crime of which 91.6% were women and 66.7% men. For the real world circumstances, 60% of the participants rated surveillance from outdoor spaces as safest while 20% preferred window surveillance. The remaining 20% rated ease of access as the key determinant in fear of street crimes. Thus majority of the participants preferred occupants of the neighbourhood to provide surveillance from outdoor spaces. On the contrary, 63% of the participants expressed comfort providing surveillance through windows and only 26% favoured their guardianship through outdoor spaces.

The section two of the questionnaire that through virtual world models studies the visual preferences of participants, proved that the geometry of architecture do impact the spatial preferences of users. As per the hypothesis and in accordance to the isovist calculations option 2 and 1 were rated very low with option 1 perceived to be the least safe. But, option 6 was perceived a safe building only next to option 4 as against the hypothesis and the isovist predictions. Similarly option 5, though in isovist surface area calculation showed greater

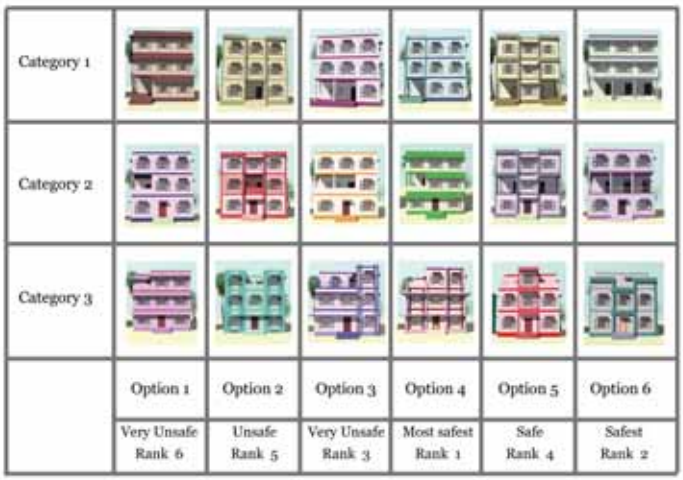

Figure 3. General safety and security perception rating.

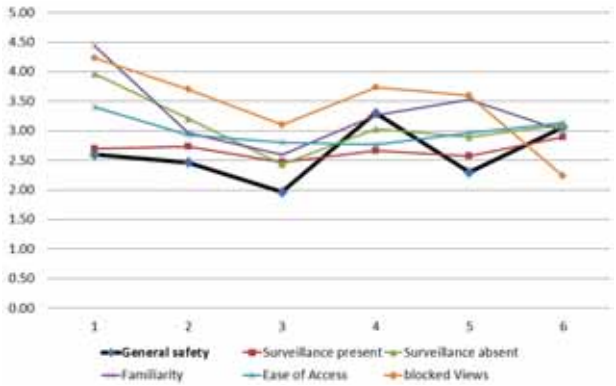

Figure 4. Impact of the different variables on General safety perception – Ground Level.

prospect, was rated the last in the double block subtraction and was ranked below option 3 (Figure 3).

The general perception of safety and security for each option was compared with variables like visibility, natural surveillance, ease of access, building familiarity and hiding spots (Figure 4, 5 and 6). Results show that the perception of blocked views, where clear line of sight were blocked by vertical walls, highly impacted perception of safety and were evidently seen to alter the rating values.

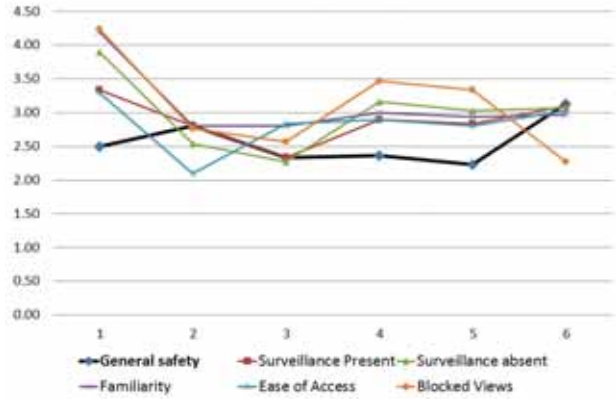

Figure 5. Impact of the different variables on General safety perception – First Level.

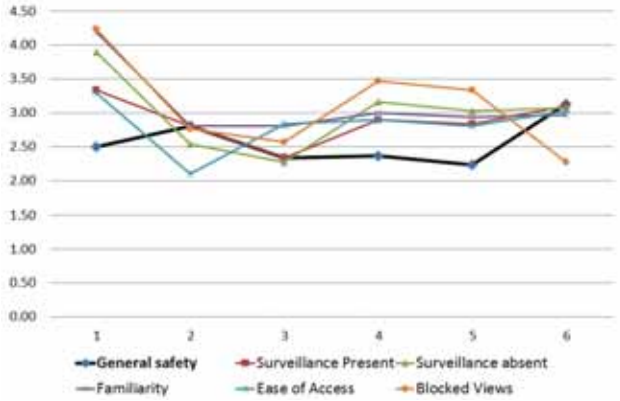

Figure 6. Impact of the different variables on General safety perception – Second Level.

Ease of access and degree of openness also altered the rating values considerably showing the degree of impact it has on people's perception of fear of crime.

5. Discussion

The experiments presented in this study investigated interrelations between spatial properties of environments on the one hand and spatial experience and behaviour on the other hand. The study mainly targeted the architects, as their visual preferences depend on their understanding of the spaces even in image based

representations. Overall, the participants showed remarkably a good evaluation of the outdoor spaces in terms of the sense of security it offered. The basic initial hypothesis that the size and location of the building outdoor spaces alters the user's perception of security stands proved by the result. The visibility analysis captured behaviourally relevant environmental properties that support the result in few cases. But there are conflicts in certain other cases. Questionnaire survey of this study points out that the participants' value familiarity and building design in terms of prospect refuge more than visibility.

6. Conclusions

The case study supports the hypothesis that people's perception of safety and security is tuned to the way in which the building fenestrations and its outdoor spaces structure their visual fields.

Due to the limited number of tested models and the specificity in terms of the building type, building use etc, further studies have to test the general validity of these findings in different types of spatial settings as well as for a broader range of built structures. In continuation to this study, experiments are being repeated using computer generated parametric models, for various other component parts of the building and several other attributes of the building features, to study the impact of building elements in isolation, before being modelled into a 3D urban space. These findings suggest that further experiments translating the qualitative descriptions of theories such as "prospect and refuge", "defensible space", "territoriality/proximities" into empirically testable hypotheses can provide valuable data to verify them as well establish relationships between them.

References

Benedict, M. L.: 1979, To take hold of space: Isovists and isovists fields, *Environment and Planning B*, **6**, 47–65.

Crowe, T. D.: 2000, *Crime Prevention Through Environmental Design: Applications of Architectural Design and Space Management Concepts,* Butterworth-Heineman, Woburn, MA.

Cozens, P. M., Saville, G. and Hillier, D.: 2005, Crime prevention through environmental design (CPTED); a review and modern bibliography, *Emerald*, **23**(5), 328–356.

Cozens, P.: 2002, Sustainable Urban Development and Crime Prevention Through Environmental Design for the British City. Towards an Effective Urban Environmentalism for the 21st Century, *Cities*, **19**(2), 129–137.

Desyllas, J., Connoly, P. and Hebbert, F.: 2003, Modelling natural surveillance, *Environment and Planning B: Planning and Design*, **30**(5), 643–655.

Geason, S. and Wilson, P. R.: 1989, Designing out crime: Crime prevention through environmental design, Australian Institute of Criminology, Canberra.

Gehl, J., Kaefer, L. J. and Reigstad, S.: 2006, Close encounters with buildings, *Urban Design International*, **11**(1), 29–47.

Guney, Y. I.: 2007, Type and typology in architectural discourse, *Journal of the Institute of Science and Technology of Balıkesir*, **9**, 3–18.

Jacobs, J.: 1961, *The Death and Life of Great American Cities*, Random House, New York.

Moffat, R.: 1983, Crime prevention through environmental design – a management perspective, *Canadian Journal of Criminology*, **25**(4), 19–31.

Newman, O.: 1973, *Defensible Space: Crime Prevention Through Urban Design,* MacMillan, New York.

Sorensen S., Hayes J. G. and Atlas, R.: 2008, Understanding CPTED and Situational Crime Prevention, *in* R. I. Atlas (ed.), *21st Century Security and CPTED – Designing for Critical Infrastructure Protection and Crime Prevention*, Auerbach, Boca Raton, FL, 53–78.

Welsh, B. A.: 2009, *Making public places safer: surveillance and crime*, Oxford University, New York.

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MANGA ARCHITECTURE

Developing architectural narratives

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Abstract. Bi-tonal and non-photorealistic architectural depictions can be employed to develop a narrative that engages the reader with both visual aspects and other emotional reactions. Using this story-telling approach to communicate architectural design is subsequently not only represented through its factual dimensions of length, width and height, materials, structure or technical details, but is extended to intangible sensorial realms, which gains special value for laypersons and professional alike. This paper presents how architects and laypersons develop a narrative of their architectural design proposals or concepts using a visualisation and story-telling tools that generates designs akin to Japanese cartoons or manga. Our paper presents the methodology, the instruments used and highlights on the base of representative samples of how narrative bi-tonal depictions of architecture contributes to the overall understanding of an architectural design and how non tangible factors aid the designers in their communication.

Keywords. Digital manga; architectural depiction; visual communication; story-telling.

1. Introduction

An architectural narrative is the main methodology which architects used to present their design to their clients. Computer Aided Design (CAD) tools has progressed significantly in the past decades and architects now often use them to generate depictions that comes in the form of photo-realistic rendering, video walkthroughs, or a series of computer-generated diagrams, while there are fewer and fewer hand sketches or bi-tonal images. However, to communicate the design to a wider audience and to allow a layperson to better grasps the elements of architectures, a different form of presentation can be supplemented. Digitally generated, bi-tonal, non-photo-realistic depictions provide another realm for representing drawings, architectural

designs and photographs. Japanese comics -manga- where the artists lay multifarious screens to express different semantics, is related to conventional architectural drafting with their various a black and white (b/w) patterns and representations. The technique of a narrative also provides a stronger personal engagement and legibility to non-professionals. In this paper, we will present the ease of generating manga architectural narratives and how they can be used as a form of architectural presentation as well as tool to help generate design ideas in the first place.

2. Traditional to Digital Manga Depiction

Manga has been widely known as a medium to narrate a story to reader. The task of drawing a manga series is however, rather tedious, time- and labour- intensive, especially when large amount of irregular regions exist.

A system that automatically draws architectural depictions using manga techniques was therefore created, called *Manga-Me* (Qu et al., 2008). Although there are numerous tools available to convert any input image, sketch or drawing into a bi-tonal manga screening, the generated hatching or halftone images does not look like traditional manga compares to the image generated by the system (Figure 1). Manga-Me is an *iPhone*-application (Manga-Me, 2010) that allows users to blend from a photorealistic to an abstract depiction of architecture using a distinct expression of manga style visual communication. The system is described in Schnabel and Qu (2011).

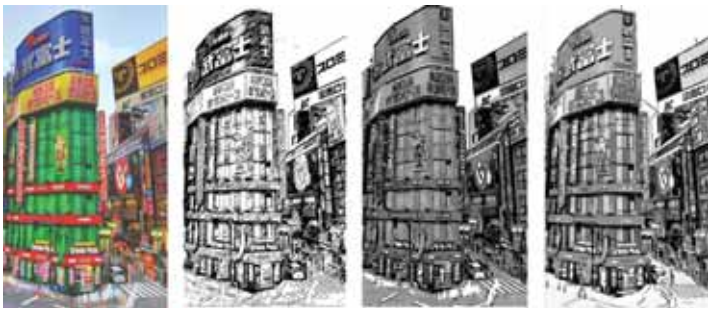

Figure 1. (From left) Original image, Hatching, Halftone, Manga-Me solution.

3. Rendering Bi-tonal Architecture Depiction

The current mainstream method of presenting an architectural design idea or concept is with photorealistic picturesque depiction of the design. The main idea is to provide a realistic impression of the building design before it is built. As seen in

most architecture books and magazines, they are a series of images that are so real; it is difficult to differentiate it from a photograph. However, architectural spatial concepts such as geometry/composition, threshold, proportion/scale, circulation/duree, light/shadow and tectonics are lost in the colourful well-rendered details and impressions. Compared to architectural images sketching in the past where these architectural elements, properties, functions, or materials are commonly represented by standardized screens, hatches, line-types, -styles, and -widths, one can easily realised drawings, sketches, and diagrams can translate architectural spatial concept clearer. Our technique allows for the development of a new generation of architectural design communication that reaches beyond graphical standard depiction of architecture and including intangible elements and expressions.

Conventional rendering presentations missing a crucial element in their communication: the missing narrative. A series of images, collages, diagrams, photographs or rendered images do not provide the reader any clue about how the design comes about, how it blends into the urban environment, how the building functions, and especially how emotions, atmospheres or expressions relate to the design. Standardised depictions provide the outlook and practicality of the building only. Digitally generated, bi-tonal, non-photorealistic depictions are increasingly becoming popular around the world as a mean of expression because of its distinct graphical quality with its elegant use of rich set of screens, tidy and fine drawing styles of b/w drawings, and its engaging ways of storytelling (Schnabel and Qu, 2012). For example, the commonly used software *SketchUp*™ provides a few additional options that change the line style of a model, giving it a unique raw outlook, mimicking hand-sketching, in order to portray architecture in a simple outlook with just its basic geometric elements. The *Bjarke Ingels Group* (BIG) is a Copenhagen and New York based group of architects, designers, and theorists operating within the fields of architecture, urbanism, research and development. Based on the idea of storytelling, their book 'YES is More' (Ingels, 2009) introduces their works through the format of a comic book. It is a playful gesture to make architecture accessible and less formal. BIG ads speech bubbles and overlaid diagrams to their architectural designs, making them appear to be alive and talking to the reader. Although most images are simple photographs, yet the overall style is novel to how they convey architectural ideas and designs to the general public and professionals alike. Akin to this, our architectural manga goes even further to give architectural representations an enhanced immersion that goes beyond conventional architectural depiction.

4. Manga Architectural Narrative

A cohort of fifty of second year undergraduate- and thirty first year master of architecture students created an architectural narrative based on manga. The aim

was to introduce the newly opened building of their School of Architecture (AIT), at the Chinese University of Hong Kong (CUHK), or alternatively capture the particular urban setting of a high density and vibrancy neighbourhood in Hong Kong, called Mongkok. They used the free Manga-Me application, which converts photographs (e.g. taken by the phone itself) into manga images. Students then used the converted bi-tonal images to lay them out on maximal two panels by using either typical manga templates (predefined subdivisions and image frames of pages) or their own generated layouts to generate a short architecture story. The pages were uploaded onto a social network group (CAAD@CUHK, 2012) for comments dissemination and evaluation among a larger audience. This not only inspired other students, but also generated variations and sequels to emerge.

Figure 2 show the initial representative outcomes of the above described manga-task. The outcome was promising as students were able to utilize the unique quality and characteristic of manga to narrate a certain story or journey that is closely related to architecture. These examples act as initial framework of how designers use the medium to develop an architectural manga digitally.

The manga-based representations of design can facilitate learning various theatrical and practice design aspects. Hereby the methodology can be a semiotic resource in learning and help learners see factual relationships together with projected, intangible elements to their designs (Herbst et al., 2011; Tatalovic, 2009).

The above descried method allows a different understanding and reflection of the sites. In conventional site analyses designers collect a variety of data that are related to the site, though they are often not used any further in their design activities. The plot of a narrative is comprised of a series of "things that characters do,

Figure 2. left: Walkthrough by Winnie Tam portraying her personal story of the AIT-building. Right: Motion supported manga by Kenton Sin: it depicts the seemingly chaotic arrangement of the urban setting and their impact on humans' movements through the streets of Mongkok.

feel, think, or say" (Dibell, 1988). Hereby each of the events must be important to the outcome of the story. A list of events or incidents alone is not a plot. The events must be "significant events" rather than a simple series of things that happen. Students are sometimes confused, however, by the difference between a series of events that happen at their site and the key elements that are significant to the story of the site. In our exercises, students select their own topics for their personal narratives and then generate a comic-strip to reinforce the structure of their narratives. Finally, in their next steps of reacting architecturally to their findings presented in their manga students generate their own de-signs based on the comic strip prewriting activity, keeping the elements of a narrative not only in mind but also as their influential design parameters.

5. Design Ideas and Presentation

The students were then given the freedom to insert the use of the manga application into any stage of their architectural design process. This section shows the various stages at which the manga application is used and in which way. Details of the posting can be found at the course social network websites *CAAD@CUHK* (2012) and *Ornaments and Patterns* (2012).

5.1. FORM-FINDING

The manga presented in Figure 3 below demonstrates how the application gives the student a different perspective in her studies of the urban fabrics. By removing the colours of the original scene, the application enhanced the overall patterns of the urban setting and made them more distinct. The student made use of this by basing her further design development on the found patterns.

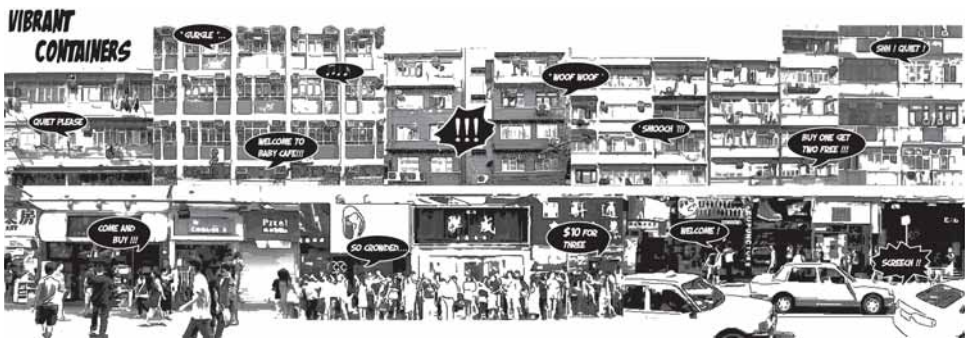

Figure 3. Design by Anita Au: form generated from the studies of urban functions.

5.2. FAÇADE STUDY

Figure 4 further below shows how a student uses a very similar visual study technique to generate a façade that construct a dynamic out of the elevations of the urban setting. By extracting, outlining and then overlaying the layers of patterns, a unique façade system that can blend into the seemingly chaotic Hong Kong urban setting is created. This is possible due to the monotonous yet rich screening of the images generated by the manga application.

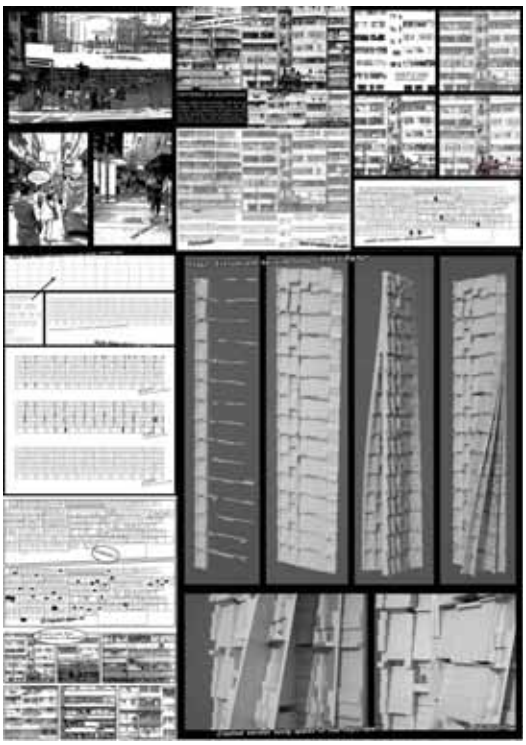

Figure 4. Design by Esther Lam: façade studies using the Manga App as base for her design.

5.3. PATTERN ABSTRACTION

The application also provides great opportunity and inspiration which allows students to use them as a form of abstraction. The next following author fully utilise the pattern that is visualised from the manga-generated image as a source of inspiration for her design (Figure 5).

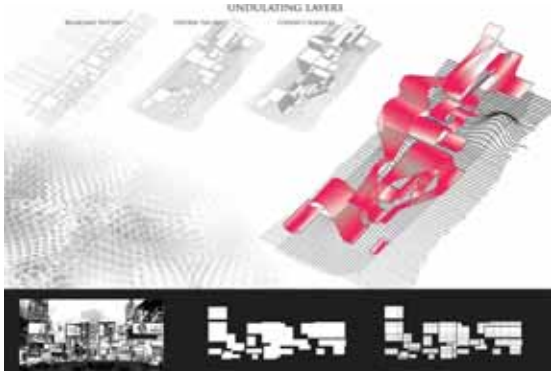

Figure 5. Design by V. Ou-Yang: Pattern developed from images created by the Manga App.

5.4. NARRATIVE

Students used the methodology of manga to present their design in a different way. Instead of plan, section and elevations, the development of their design and its details became the central element of their design communication (Figure 6). Hereby they used not only a bi-tonal representation of their design, but transferred their experiences gained through the manga methodology to put a narrative into their design communication.

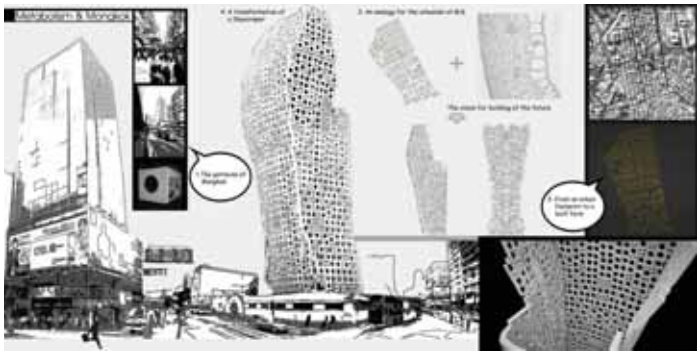

Figure 6. Design by Leo Yu: Using manga as basis to narrate his final design.

5.5. FINAL PRESENTATION

The clear line drawing and simple screening of manga allows designers to use this method as a tool for their final design presentation. The result is simple and clean

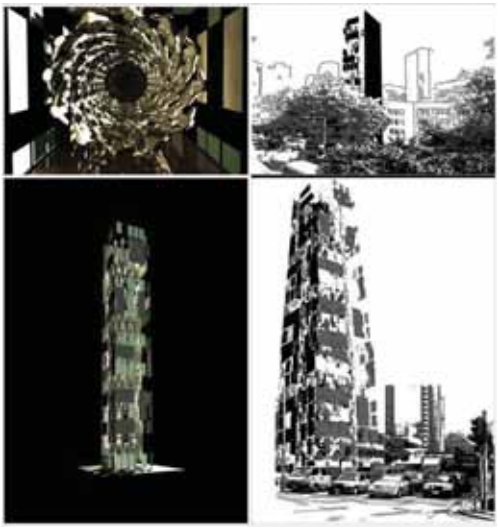

Figure 7. Design by Mark Choi: Using site images created from manga apps for final design.

providing a narrative of how the design is formed and how it is related to the site context (Figure 7). The author used the narrative of his design development as methodology to present and explain his design.

5.6. MANGA AS DESIGN METHODOLOGY

A student takes up the challenge of using Manga as the main design methodology and aiding tool instead of just using it in one part of the design process (Figure 8). From site study to form exploration all the way to the final presentation, she generated the form that fits the manga character as well as reactive to the site context. This demonstrates strong possibilities with the integration of the tools and design objectives.

Although the use of Manga-Me apps was required from the students at first, it was well received and students started to rely on the apps to get design inspiration. Students use it as a third eye to get a different perspective of the site and environment. The various lines and hatches developed by the apps to overlay the photograph bring out distinct architecture elements which are not captured with a normal camera. Furthermore, students are challenged in terms of design presentation. Instead of a normal perspective rendering, elevation, section, students use a sequence of images to tell a story of their design. This method requires designers not only to represent their designs factual, but also representational with intangible parameters to generate and present their ideas.

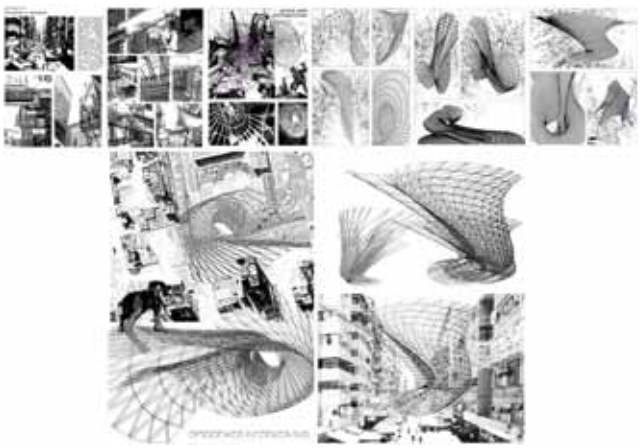

Figure 8. Design by V. Ka: Using manga throughout her design process.

6. Conclusion and Future Research

We have demonstrated that with the use of the Manga-Me app to create bi-tonal, non-photorealistic images, the result can be exhilarating. The additional point-of-view not only provides architects new ways to look at the site context and architectural elements, it also gives them a clearer means to communicate their design with a layperson. The technique is efficient and convenient in use in architectural design and its communication. Hereby architectural design communication is extended to a genre that is not only popular and commonly accepted, but also carries rich and meaningful content that merges sketching and digital drafting.

This provides us with the opportunity to use this application as an architecture educational tool. Especially in the context with social networks, which allows a larger dissemination, evaluation and commenting, allowing for innovative communications and narratives to happen. With its clearer depiction of architecture elements, this will provide easier understanding of how building designs are generated and developed. Moreover, the hatching details can teach students how to do hand sketching to bring out specific characteristics of their design. This 'reverse engineering' of sketching has the potential to blend over the education of digital and analogue design communication in architectural design.

Akin to Calderon et al. (2006) and Ng et al. (2006) we plan in our future research to address cinematic aspects of our architectural digital manga visualizations and generate animation techniques allowing designers to create architectural animations based on bi-tonal non-photorealistic depictions with the same ease as conventional animation methods.

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References

Ingels, B.: 2009, *Yes Is More: An Archicomic on Architectural Evolution,* Bjarke Ingels Group, Evergreen, Taschen, UK.

"CAAD@CUHK": 2012, Available from: Facebook Group of School of Architecture, CUHK, <http://www.facebook.com/groups/CAADATCUHK> (accessed on 1 December 2012).

Calderon, C., Nyman, K. and Worley, N.: 2006, The architectural cinematographer: creating architectural experiences in 3D real-time environments, *IJAC*, **4**(4), 71–90.

Dibell, A..: 1988, *Plot,* Writer's Digest Books, Cincinnati, OH.

Do, E. Y-L. and Gross, M. D.: 1997, Inferring design intentions from sketches: An investigation of freehand drawing conventions in design, *in* Y-T. Liu, J-Y. Tsou, and J-H. Hou (eds.), *Proceedings of the Second Conference on Computer Aided Architectural Design Research in Asia*, CAADRIA, Taiwan, 217–227.

Goldschmidt, G.: 1991, The dialectics of sketching, *Creativity Research Journal*, **4**(2), 123–143.

Herbst, P., Chazan, D., Chen, C-L., Chieu, V-M. and Weiss, M.: 2011, Using comics-based representations of teaching, and technology, to bring practice to teacher education courses, *ZDM*, **43**(1), 91–103.

"Manga_Me": 2010, Available from: iPhone Application Computer Science and Engineering Department, CUHK, <www.manga-me.tk> (accessed on 1 December 2012).

Nagatomo, H.: 2003, *Draw Your Own Manga: All the Basics*, Kodansha International, Japan.

Ng, K., Schnabel, M. A. and Kvan, T.: 2006, Architectural animation becomes alive: creating spatial narrative with spatial characters for animations, *in* V. Bourdakis and D. Charitos, (eds.), *Proceedings of the 24th eCAADe Conference*, eCAADe, Volos, Greece, 598–603.

"Ornaments and Patterns": 2012, Available from: Facebook Group of School of Architecture, CUHK, <http://www.facebook.com/groups/OandP> (accessed on 1 December 2012).

Schnabel, M. A. and Qu, Y.: 2012, Digital Manga Virtual Environment, *in* T. Fischer, K. De Biswas, J. J. Ham, R. Naka and W. X. Huang (eds.), *Beyond Codes and Pixels: Proceedings of the 17th International Conference on Computer-Aided Architectural Design Research in Asia,* Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Chennai, India, 619–628.

Schnabel, M. A. and Qu, Y.: 2011, Digital Manga Depiction *in* C. M. Herr, N. Gu, S. Roudavski and M. A. Schnabel (eds.), *Circuit Bending, Breaking and Mending: Proceedings of the 16th International Conference on Computer-Aided Architectural Design Research in Asia,* Association for Computer-Aided Architectural Design (CAADRIA), Newcastle, Australia, 741–750.

Tatalovic, M.: 2009, Science comics as tools for science education and communication: a brief, exploratory study, *Jcom,* **8**(4), A02, 17 pp.

Qu, Y., Pang, W-M., Wong, T. T. and Heng P-A.: 2008, Richness Preserving Manga Screening, *ACM Transactions on Graphics*, **27**(5), 155:1–155:8.

Qu, Y. and Schnabel, M. A.: 2009, Drawing Architecture using Manga Techniques, *in* A. Dikbas, E. Ergen and H. Giritli, (eds.), *Managing IT in Construction / Managing Construction for Tomorrow*, CIB W78, CRC Press/Balkema, Istanbul, Turkey, 567–576, 2009.

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DECODING PASSURA'

Representing the Indigenous Visual Messages Underlying Traditional Icons with Descriptive Grammar

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Abstract. For the Toraja people in South Sulawesi, Indonesia, the engraved ornament (Passura') means more than a simple decorative element. More importantly, Passura' also serves as a symbolic icon to convey spiritual messages. However, only few people actually understand the underlying meaning behind the ornament. Consequently, those without this knowledge can only appreciate the aesthetic dimension of Passura'. Our computational design research focuses on understanding the visual–linguistic aspect of Passura' using Descriptive Grammar method to investigate how meanings are embedded on the ornaments. The design rules and their description are synthesized into a shape-to-text grammar that can read the ornament as a text, and into a text-to-shape grammar that can write a text into an ornamental design. Preliminary results of this grammar demonstrate how Passura' works as an active indigenous communication device, rather than simply being a passive decorative element.

Keywords. Passura; ornament; shape grammar; Toraja.

1. Introduction

This paper investigates the association of Passura's design with its symbolic description using computational design method. In particular, we analyze the emergent quality of Passura' design using Shape Grammar (Stiny and Gips, 1972) to analyze and synthesize the generative aspect of the design. We also analyze the relationship between shape and its description using Descriptive Grammar (Stiny, 1981), a generative description method to associate a description of design with its design rule. Passura' designs mostly take inspirations from animals, plants, folklores, household tools, and other natural/man-made objects that are considered

Figure 1. Passura' and the engraving process.

important for the Toraja people (Figure 1). There are about seventy design-types that remain to be widely used in today's traditional ceremonies, crafts and traditional house. Although Passura' can be considered as pictograms or ideograms, the pictorial messages in Passura' are not always as obvious as in other glyph. The shapes are not to be read phonetically as a letter like Chinese characters or Hieroglyph, or as a number like in some Mayan glyph. It is this subtlety that makes Passura' unique, where the relationship between shape and its description could be one-to-many, many-to-one, or one-to-one.

In order to reason and represent this subtlety, first we will approach it from the visual to the textual by analyzing the design rules with shape grammar, and then map the pertaining symbolic description with descriptive grammar. Second, we will move from the textual to the visual by synthesizing the rules into a shape-to-text grammar that can read the ornament as a text, and into a text-to-shape grammar that can translate a text into an ornamental design.

2. Passura' Grammar

The available literatures of Passura's design (Kadang 1960; Pakan 1973; and Sande, 1989) are mostly served as an iconographic catalogue to descibe the symbolic meanings of the ornament. However, there is very little explanation about

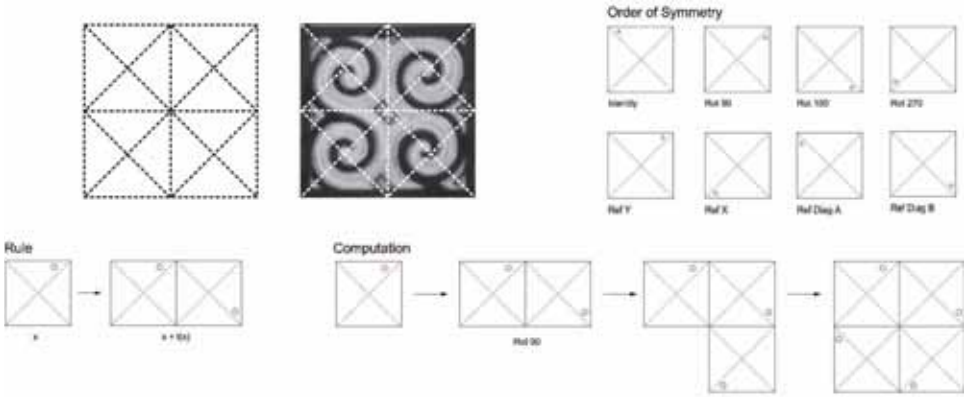

Figure 2. Rules to generate Basic Grid.

how their shapes are generated. Based on our observation and interview with several local engravers in Toraja, we found that there are certain procedures to generate the ornament.

To start with, Passura' designs are mostly developed on top of two overlapping 90° and 45° rectilinear grids (Figure 2).

We represent this grid as an assemblage of a square module that has eight orders of symmetry, i.e. eight different ways of transforming the square back into its original shape using four rotation angles and four reflection planes. With this symmetry, there are eight different basic designs that can be generated from one spatial-relationship. Figure 2 shows an example of one basic design computation with rule $x \rightarrow x + t(x)$. Based on this grid rule, we then develop design rules in two stages: first is to define a rule that produce a modular shape (Lg), and second is to define rules that generate various design compositions using this modular shape to finally create new ornaments (L_G).

2.1. MODULAR RULES

Here, we limit our study to analysing only one ornament shown in Figure 2. Using a rectangle as an initial shape, rule g generates the spiral in the ornament by adding a scaled and rotated shape and then subtracting part of the initial shape (g: $x \rightarrow t(x) + prt(x)$). The shape has three parameters where a1 = Scale Factor (float), a2 = Degree of Curvature (integer), and a3 = Rule Steps (integer). With these properties, the proportion of a new shape can be defined. For instance, to create an Archimedes Spiral, a1 would be 0.618 (Figure 3).

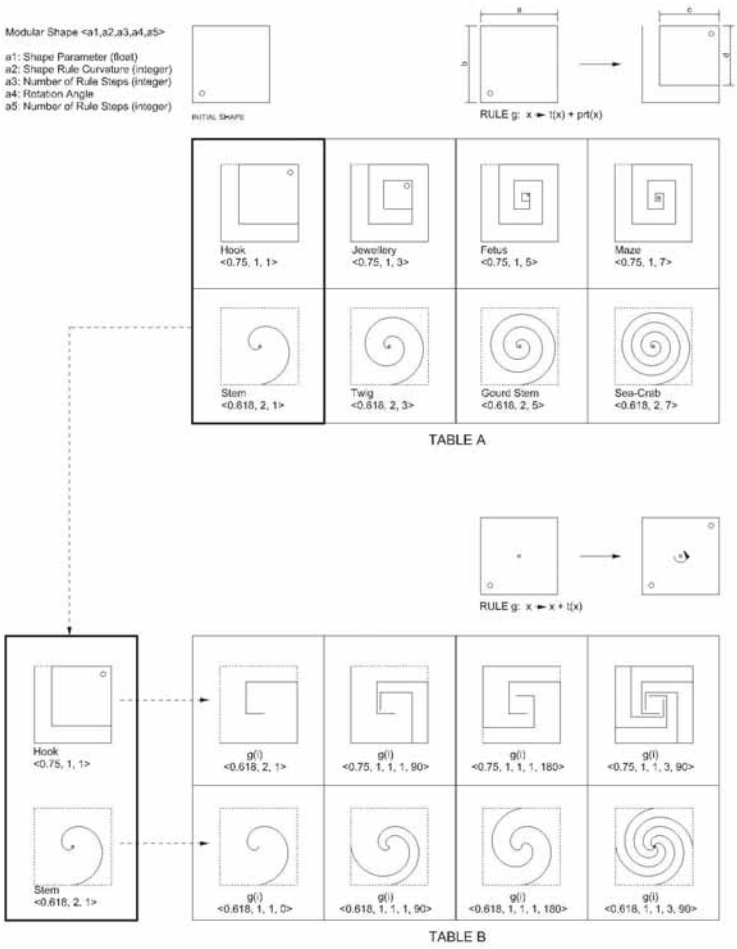

Figure 3. Parametric Rule to generate Modular Shape.

As seen in Figure 3-table A, the above rule can generate shapes that symbolize particular objects in Toraja as the shape parameter is varied, e.g. 'hook': <0.75, 1, 1> or 'stem': <0.618, 2, 1>. This shape-description association can be registered with a function $g_i \rightarrow d_i$, where d_i is the description of the shape and g_i is a rule that generates the shape. The two shall be encoded in a list $\{d_i: g_i\}$ for future use. The shapes shown in Figure 3-table B are examples of various shapes that can be computed sequentially from the leftmost shapes in table A. In this example, the shapes 'hook' and 'stem' serve as initial shape to generate new designs with rule $x \rightarrow x + t(x)$, where each of the newly-constructed shape is made to overlap with

the initial shape. This rule has an extra two parameters: a4 = Rotation Angle (Float) and a5 = Rule Steps (integer)

While some shapes L_g can be considered as one ornament, others can also serve as a sub-shape for the composition rule described in section 2.2.

2.2. COMPOSITIONAL RULES

To generate a certain ornament, a modular shape from the previous stage ('stem') is placed within the grid module as a carrier, and defines the basic spatial relationship. The modular shape follows the carrier's order of symmetry and results in eight different rules. Figure 4 shows a number of different strategies

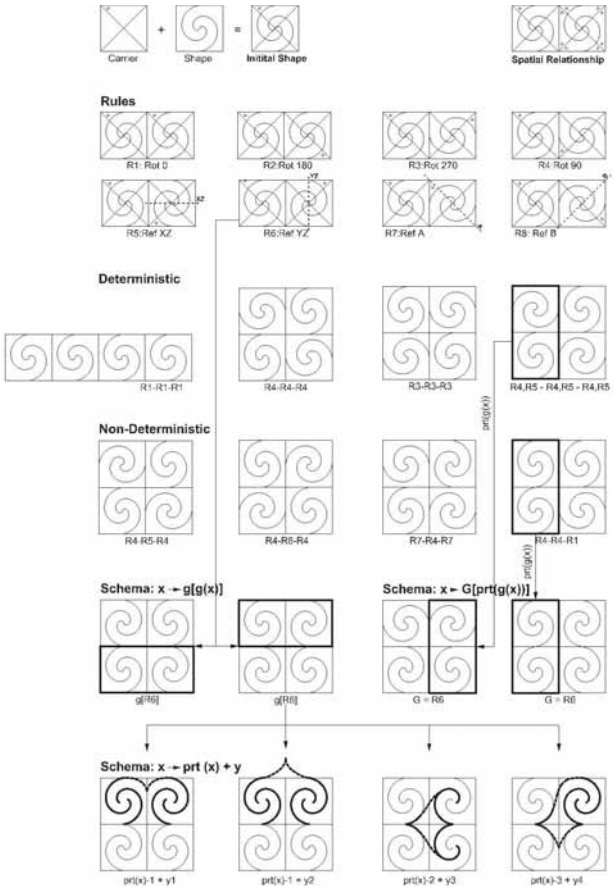

Figure 4. Different types of Compositional Rules generate ornament from modular shape.

in generating the ornament by defining the rule sequence, and by using the shape that emerges from the computation (see Knight (1999) for more different types of rules, and Knight (2003) for more computing with emergent shape):

Rule Sequences: A rule can be used deterministically, where only one rule is applied to the new shape at each step, for instance, R1-R1-R1-R1. A rule can also be used in a non-deterministic way, where two or more rules ordered in particular sequence are applied to the new shape or any other previous shapes, e.g. R1-R2-R1-R2. Different types of rule sequence would extend the number of possible basic design from m^n deterministic basic designs to mn non-deterministic basic designs (m = order of symmetry, n = number of iteration).

Emergent Shape: In order to capture the use of emergent shapes, we show a set of examples involving several schemas: g[g(x)], g[part(g(x)], and x → prt(x) + y. Schema g[g(x)] will repeat rule x → x + t(x) on the very shape that it generates. As an example, a design from rule R6 is used as an initial shape to generate two new designs with the same rule R6. In the other two examples, only part of the g(x) design is used as an initial shape, hence g[part(g(x)]. Furthermore, schema x → prt(x) + y will retrieve part of x and then add a new shape (y), allowing us to embed a new emergent shape that intuitively resembles a particular object. Based on the Passura catalogue (Sande, 1989), we associate four different descriptions for the new emergent shapes, i.e.: 'rice', 'buffalo', 'creese' and 'banyan leaf', with a function $L_G \rightarrow d_i$.

Based on this strategies, we define six properties for this grammar <a1, a2, a3, a4, a5, a6> : a1 = Initial Shape Parameter (list), a2 = Spatial Relationship (string), a3 = Rule Sequence (string), a4 = Rule Steps (integer), a5 = Embedding (string, integer) and a6 = Part Embedding (integer).

2.3. ENCODING PASSURA' AMBIGUITY

As can be seen from the previous analysis, Passura' design and its description may have an ambiguous relationship: one-to-many, many-to-one, or one-to-one, as illustrated in Figure 5.

When the design is being generated, most Passura' have one-to-many relationships with the source object. The basic initial shape can be used to generate many different kind of shapes in set L_g using the parametric-rule shown in Figure 3. Furthermore, the compositional rule strategy (i.e. rule-sequencing and embedding) could further generate enormous number of possible new designs in the set L_G. At the shape and description mapping stage, the emergent design in set L_g is encoded to the pertaining descriptions in a one-to-one relation. However, the description function g → d can be used recursively to recognize objects (d) from other branch of the design (G). For instance, there could be other shapes in set L_g that looks

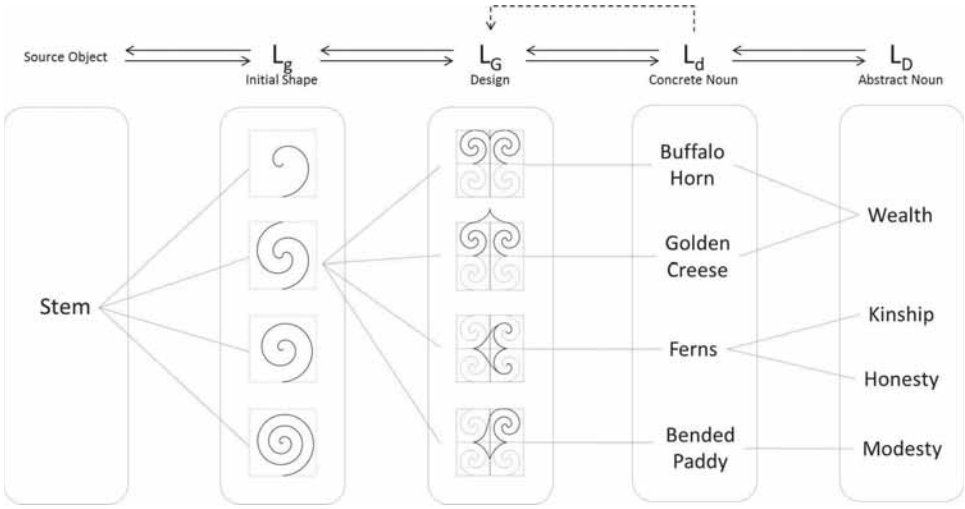

Figure 5. Text-to-Shape and Shape-to-Text Relationship diagram.

like a 'buffalo'. At the description domain, the relationship between the concrete noun and the abstract noun may vary. Two different nouns, e.g. 'buffalo' and 'creese', could be mapped into one abstract noun, i.e. 'wealth' as they are both considered a luxury and prestigious object in Toraja. In contrast, the concrete noun 'a branch' may also have two different meanings 'kinship' and 'honesty'. There are also some cases where one noun has exactly one meaning (e.g. bended paddy → modesty).

This ambiguous relationship can be encoded with the function $\{G_i : D_j \mid 1 < j < N\}$ for an ambiguous shape, or $\{D_i : G_j \mid 1 < j < N\}$ for an ambiguous description, where N is the number of possible translation. Thus the list $\{D_0: G_1, G_2\}$, for instance, means that there are two possible designs for the description D_0. This encoding system can also be used to express other ambiguous relationships. For example, the list $\{D_i : d_j \mid 1 < j < N\}$, where capital D refers to Abstract Noun, and small D refers to its concrete noun, can associate one Abstract Noun (D) to N number of concrete noun (d).

3. Passura': Text-Shape Interpreter

The relationship diagram shown in Figure 5 has a two-way direction, which means that one can use either shape or description as the starting point. After generating Passura' designs from shape to description in the previous section, in this section we will reverse the process. Using the design rules and the descriptive function,

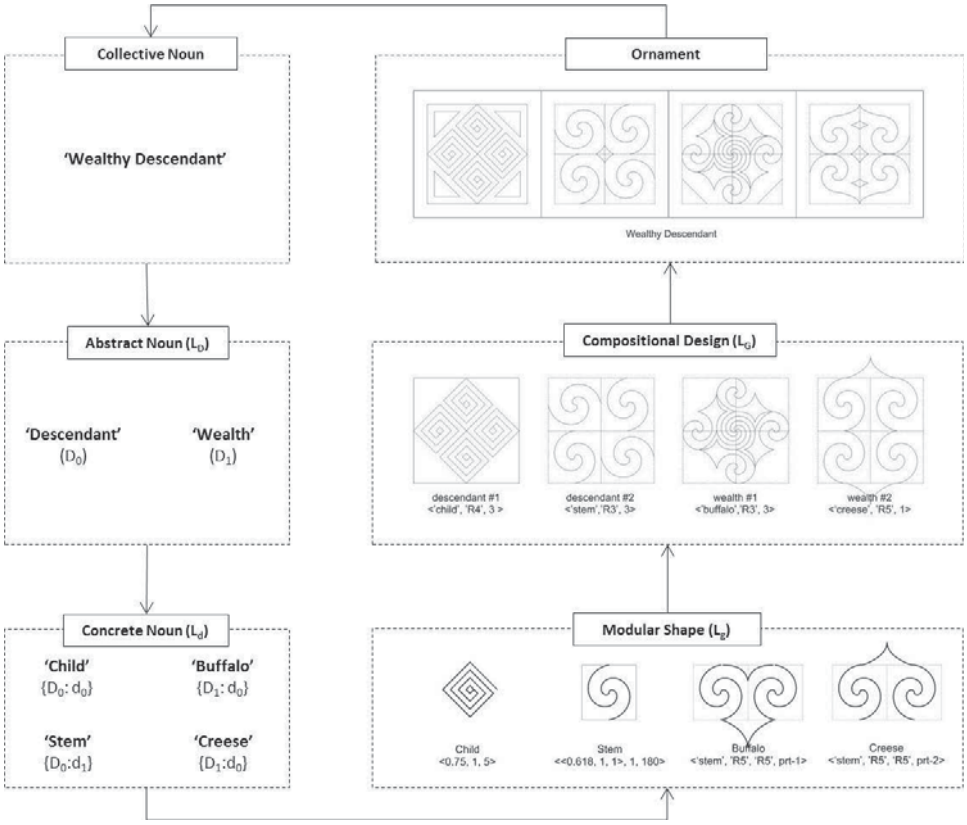

Figure 6. Translation from description into hypothetical design.

we generate the ornament with some text as an input. Suppose that a person wish his/her descendant to be endowed with some wealth: a 'wealthy descendant' as described in Figure 6. A collective noun 'wealthy descendant' consists of two abstract nouns: 'wealth' and 'descendant'. We derive these abstract nouns into two possible corresponding concrete nouns: 'wealth' with 'buffalo' and 'creese', and 'descendant' with 'child' and 'stem'. To define the modular shape, we use the function $L_d \rightarrow L_g$ to call the modular and compositional rules (g_n) that match the concrete nouns (d_n) as follows:

- $\{D_0: d_0\} \rightarrow$ 'child' : <0.75, 1, 5>
- $\{D_0: d_1\} \rightarrow$ 'stem' : <<0.618, 1, 1>, 1, 180>
- $\{D_1: d_0\} \rightarrow$ 'buffalo' : <'stem', 'R5', 'R5', prt-1>
- $\{D_1: d_1\} \rightarrow$ 'creese' : <'stem', 'R5', 'R5', prt-2>

This descriptive function generates modular shapes in the set L_g. Note that the shape 'stem' has more properties than the shape 'child' since it is essentially the first derivation of the shape 'child' with different curvature and less rotation. The last two arguments (1 and 180) transform the shape by copy-rotating it 180 degrees once. Also notice that the shape 'buffalo' and 'creese' have more properties because they are the second derivation of the shape 'stem' (i.e. the 'stem' properties are nested in their first argument). Their properties are also similar because they both use the same emergent shape, but with different parts (i.e., prt-1 and prt-2).

With these shapes, we use the grammar from compositional rules to generate design that could express 'descendant' and 'wealth'. The design (L_G) and the description are then encoded with the descriptive function $L_G \rightarrow L_D$ in the list $\{Di : Gj \mid 1 < j < N\}$ as described below:

- 'descendant' #1 : <'child', 'R4', 3> → $\{D_0: G_1\}$
- 'descendant' #2 : <'stem','R3', 3> → $\{D_0: G_2\}$
- 'wealth' # 1 : <'buffalo','R3', 3> → $\{D_1: G_1\}$
- 'wealth' #2 : <'creese', 'R5', 1> → $\{D_1: G_2\}$

Later, this encoded list allows us to create an ornament directly from an abstract noun (LD). The ornament can be perceived as a final design (G) or as a modular shape (g) that is ready to be used for generating a new ornament using different rule-sequence or schemas with grammar (G).

4. Discussion

This paper demonstrates how Passura', as a tacit product, can be explicitly represented, analyzed, and synthesized from a text to design and from a design back to text using descriptive grammar. Examples used in this paper are hypothetical as the goal of this study is less about proving the actual design process of Passura' engraver or deciphering Passura' code, but more about representing the promising logic in Passura' design to promote its potential aspect for further semantic computational design research. This study highlights two interesting issues in exploring cultural objects using computational design methods:

- **The Explicit Aspect of Ambiguity.** Despite the ambiguity in reading Passura' design, as not all of them can be discretized into countable shapes, the descriptive grammar could help designers to encode semantic polarizations of Passura design in a more tangible manner.
- **The Nonlinear Association of Shape and Description.** The symbolization of the Passura' design does not occur in linear fashion since the description (e.g. meaning) can be assigned into the shape at any level of the computational design process, either in the case of text-to-shape or shape-to-text.

References

Kadang, K.: 1960, *Ukiran Rumah Toradja*, Dinas Penerbitan Balai Pustaka, Djakarta.
Knight, T. W.: 1999, Shape grammars: Six types, *Environment and Planning B:* **26**(1), 15–31.
Knight, T.: 2003, Computing with Emergence, *Environment and Planning B*: **30**(1), 125–155
Pakan, L.: 1973, *Ukiran Toraja: The secret of typical Toradja's patterns*, s.n., Ujung Padang, Indonesia.
Sande, J. S: 1989, *Toraja in Carvings*.
Stiny, G. and Gips, J.: 1972, Shape grammars and the generative specification of painting and sculpture, *Information Processing*, **71**, 1460–1465.
Stiny, G.: 1981, A note on the description of designs, *Environment and Planning B*, **8**(1), 257–267.

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A SHAPE GRAMMAR TO GENERATE LOGGIA RUCELLAI

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Abstract. This article shows the result of generating a 3d model of *Loggia Rucellai* in Florence using a shape grammar from Leon Batista Alberti's treatise De Re Aedificatoria and it is a test bed for further generations of buildings using Alberti´s rules. It shows the accuracy of such grammar to help tracing the degree of influence of Alberti's treatise in Renaissence Portuguese architecture. *Rucellai palace* facade ornaments and its interior loggia where used to analyze and compare the *Loggia* generation accuracy. A Grasshopper script is used for the automation of the rules derivation. An evaluation process is presented and its use aims to better understand the deviations between the treatise and the Loggia grammars.

Keywords. Alberti; shape grammars; transformations in design; grammar evaluation; digital fabrication.

1. Introduction

The research presented in this paper is part of a larger project aimed at understanding the cultural impact of Alberti's treatise on classical architecture, using a computational approach called Digital Alberti based in Coimbra University, Portugal. Namely, the project aims to determine the influence of Alberti's treatise on Portuguese architecture in the Counter-reform period.

Based on document sources that reveal links between Portuguese architects and Alberti's work, some historians have pointed that such an influence was real, but

none was able to determine its extent so far. The idea is to shed some light on this discussion by translating the treatise into a shape grammar (Stiny and Gips, 1972) and then trace the influence of Alberti's work by determining to which extent the grammar can account for the generation of Portuguese classical buildings (Kruger, 2011). This approach follows the transformations in the design framework proposed by Knight (1983) according to which the alteration of one style into another can be explained by changes of the grammar underlying the first style into the grammar of the second. The project foresees the development of grammars as showed in this article, encoding the rules for designing the column system and rules for designing buildings, namely churches and in this case a *Loggia*.

The decision to generate the *Loggia* as a target element to be analyzed was due to its physical proximity to *Rucellai palace* as seen in Figure 1. The loggia construction is contemporary to the construction of the palace. This double condition associated to a wider consensus on Alberti's *Rucellai palace* authorship set up a good test ground for the analysis and verification of the ornament, as well as the proportions used initially in the existing buildings and then in the loggia generated. It is possible that both constructions were built by the same workers, suggesting that some information was conjointed between the palace to the *Loggia* builders. Supporting the idea that there is a coherent relationship within the *Loggia* and *palace* ornament elements and proportions employed. In that way it might be possible to verify a pattern of design procedure by the Loggia architect.

This article will present the grammar for the *Loggia Rucellai*, using a grammar of the treatise centered in the Doric, Ionic and Corinthian orders as well as the

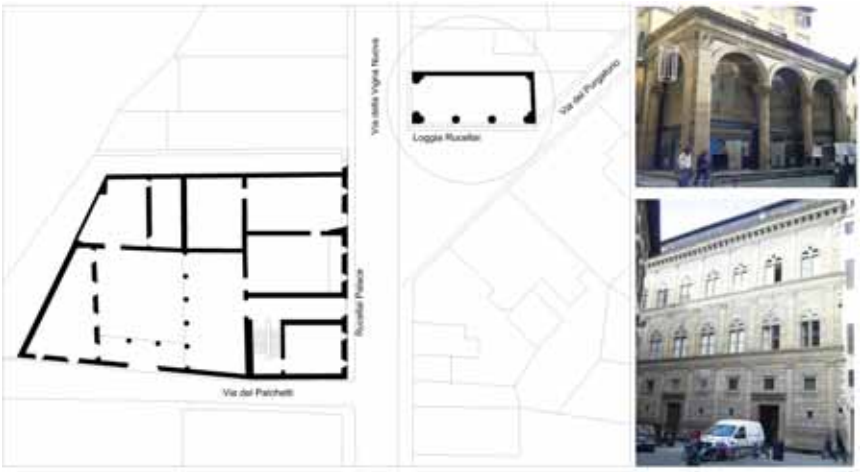

Figure 1. Loggia Rucellai and Rucellai palace.

columnate grammar sections. A sketch will demonstrate the computer implementation of such a grammar.

Since the Renaissance, the authorship of architectural design has been one of the issues under discussion among different specialists in theory and architectural history. Redefining the condition of the architect as one who operates the complex world of meaning of the elements of architecture and its "concinnitas" Alberti had repositioned the architect's activity among those liberals ones, separating him from the operative and craftsman association since medieval age. This autographic condition of the architect as Carpo (2011) has pointed out, is highlighted with construction of Renaissance buildings such as the Florence Cathedral dome, whose authorship was claimed by Brunelleschi. The indeterminacy of the authorship of the buildings assigned is related to the social, artistic and professional emancipation of the architect.

Alberti, like many other architects/thinkers operated jointly with a nucleus or guild of builders. Some of those who collaborated with him, and were directors of construction in the field are Mateo de'Pasti in Rimini, Bernardo Russelino in Florence and Luca Fancelli in Mantua. There are contradictory opinions regarding the authorship of *Rucellai palace*, many attributed to Rucellino following Alberti's concept and design with reference to his Piccolomini Palace in Pienza. We will attempt to contribute to the definition of Loggia Rucellai author/architect use of Alberti's rules present in the treatise, but not provide proof it's authorship.

The *Loggia Rucellai* is full of social meaning, as Kent (1972) said "the family loggia in the Piazza Rucellai, the first urban space of the Renaissance created for the special benefit of a powerful patron". It also provides spatial and architectural significance because it consists almost exclusively of elements of the column system. It is the column systematization per se. The construction of *Rucellai palace* started in 1448. The loggia of the palace (note that this loggia is inside the palace and served as comparative model) and its inner courtyard were concluded in 1455, as the facade of the palace began in 1461, there is strong historical evidence of Alberti's participation on the facade design. The *Loggia Rucellai* was completed in 1466 ready for the marriage of the daughter of Cosimo Medici, Nannina and the son of Giovanni Rucellai, Bernardo (Preyer, 1981).

2. The Loggia Shape Grammar

Generically this grammar is an analytic grammar and comprehends a shape grammar, a description grammar as well as a program of the target element or building to be generated.

The derivation process of the column systematization has different stages. The first stage regards an insertion of labels in a line (that may come from the site

plot); the second stage: an insertion of column base; the third stage: an insertion of shaft; the fourth stage: an insertion of a capital; the fifth stage: an insertion of *latastrum* (only when a corinthian or composite capital is in use) and arch or architrave; the sixth stage: an insertion of an entablature; and finally, the seventh stage: to insert the intercolumn. When the target element has a façade, windows and doors are the last elements to be inserted (Building stage).

Then each of the above stages has sub-stages such as: in the first stage the line may be divided in multiple points marked with labels; in the second stage the column base may be Doric or Ionic and each of those is divided in different elements (e.g. plinth, torus, fillets and scotia); in the third stage the shaft may be plain or with flutes; in the fourth stage the capitals accepted are Doric (with 2 variations) or Tuscan, Ionic, Corinthian and Composite; in the fifth stage the arches and architraves may have Doric or Ionic ornaments; and in the sixth stage the entablature may be Doric, Ionic or Corinthian. In the seventh stage the intercolumn may have an engaged or detached wall, or be empty. Finally the façade may have Doric, Ionic or Corinthian doors (2 variations: pediment and engaged or detached lateral columns), window and pedestal.

The grammars were developed as parallel grammars encompassing four views: plan, section, elevation, and axonometric (as shown in this paper due to space constrains). The function of the derivation stages is to better control the different grammars in use and ultimately to mark where the transformations occur. The first three of these views are developed in the Cartesian product of the algebras U12 and V12, and the fourth in the Cartesian product of the algebras U13, U33 and V13 such as the grammar presented in this paper. Each rule has a section containing both parameters, descriptions and, when needed, a set of functions to be coordinated with other grammars. In this article we show the rules that allow generating a colonnade and the *Loggia Rucellai*. It is given a place of insertion of columns and horizontal elements (arches and entablature) proceeding to the application of the various rules recursively to generate the *Loggia* using elements of ornament described by Alberti.

The rules consist of drawing elements and a set of descriptions. The drawings of this grammar are represented in perspective and they contain, besides the elements of the column, an axis of symmetry of the element and a label at the end of this axis comprising two parallelepiped L shapes with green colour. The function of this label is the spatial orientation and localization of the 3D model facilitating the understanding of the rule and the subsequent rule to be applied. Each rule has a set of descriptions. They are composed by defining the conditions encountered in the drawing, the parameters used for these conditions and ultimately a function that provides a framework and identify the provenance of the rule in use. This function is associated with an inference table that will manage the use of these functions relating them with the different derivation stages, providing a greater control allow-

ing the generation of grammars. One of the purposes is to control the parallel use of grammars, understanding if certain rules are being repeated or even if they do not belong to the corpus. If a rule is not employed but necessary for the generation of the element, we can then conclude which rules or set of rules or even new grammars have to be added, subtracted or transformed and in what stage are they related.

3. Implementing the Grammar and Derivation

The rule 0 assigns a line from the site plot at Via del Purgatorio in Florence (Figure 1) and divides it in 5 different segments. The bigger ones are given to generate the inter column and the rest are guide lines to generate the pilaster. The mathematical expression is such as 3D+2wPilaster+3IC = L where L is the length of the site plot and wPilaster is the width of Pilaster and D is the column diameter. IC is the inter columnio.

Rule 1 assigns a point P from the site plot line. In this point a generic column, a cylinder, is going to be positioned. Rules 2 until 7 are related with previous grammars, they are evoked from previous grammars and are assigned and articulated with a function to manage its use, not allowing it, in this case, to be repeated. This function is such as <Db><s><Cc> (rule 2) meaning <Db> a state (usually related with the final sub stage) of the generation of the Doric base grammar. <s> is the grammar of the shaft and <Cc> for the Corinthian capital. The reason for such machinery is that, according to Alberti, the user is "invited" to use various elements in any kind of order subverting the Vitruvius' logic of order type use. Rule 8 is a new rule. It is a transformation of a pilaster, being taller and in fact a union of two similar pilasters resulting in the outstanding external double corner. This pilaster is added on the corner and is related with the rule 9. Rule 9 is another new rule adding a platform with 2 steps where the entire Loggia will fit. Finally, an M rule is created; it is a rule that makes the mirror at the final steps of the generation. And an E rule erases all the labels and notations, finishing the derivation. See the rules in Figure 2 and derivation in Figure 3.

The computer implementation of the rules of the grammar was done using a Grasshopper (GH) code regarding an automation of generation. Other experiments aiming a full implementation of grammar are being carried out using Python scripting in particular and CGA applied to City Engine. However these results will be presented in further publications.

4. Evaluating the Generation

As said in section 2, this grammar has a shape grammar, a description grammar and a program to be assigned in the generation of a specific target building, in this case the *Loggia Rucellai*.

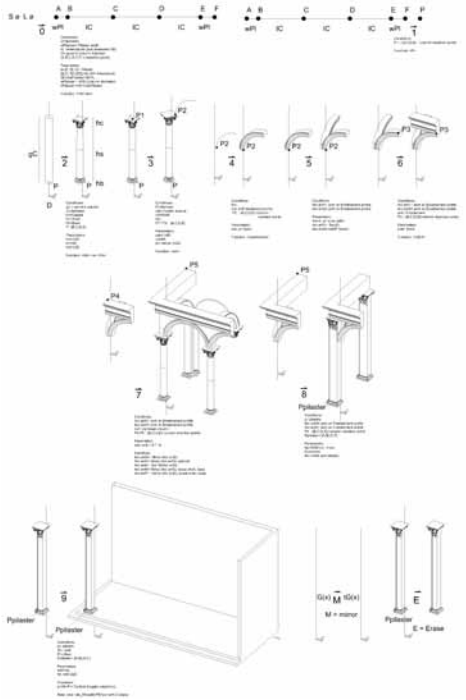

Figure 2. Loggia Rucellai shape grammar rules.

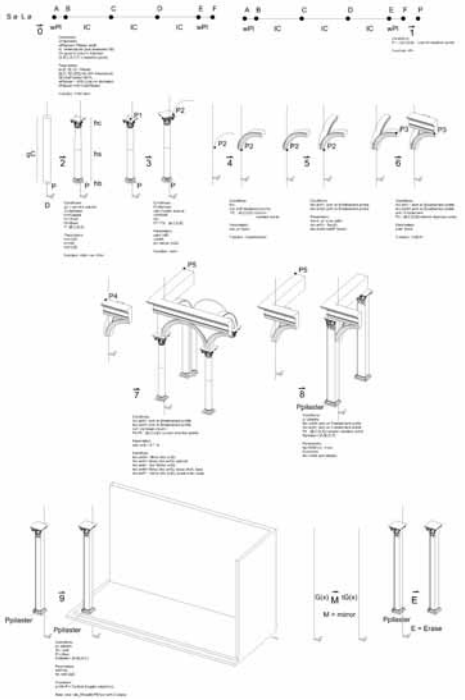

Figure 3. Loggia Rucellai shape grammar rules derivation.

The program uses mostly the list of ornament elements from the real building to be generated. The Table 1 serves to fix systematically the system elements of the column in the building in question. Then each element is checked with the ones existing in the treatise grammar. Through the overlapping of data we can get an accurate idea of elements that are added, subtracted and transformed. By analyzing them in more detail the aim is to understand, quantify and qualify the nature of those changes. A GH code was used to detect the elements not specified by the grammar as seen in Figure 5.

The comparison and evaluation process employed to generate the grammar held up by applying grammars from the treatise. One virtual artifact (3D model) was produced and subsequently prototyped gaining knowledge from this process towards the theory validation, the evidence of Alberti's treatise prescriptions use in Portuguese architecture, as Figure 4 shows.

The artifacts (3D model and a rapid prototype) obtained were compared with the real building through photographs in different perspectives as well as different details of the system elements of the column as seen in Figure 6.

Table 1. Existing elements at Loggia Rucellai Building.

Loggia Rucellai		
Main facade	**Lateral facade 3st floor**	**Interior Loggia**
2stepsplatform/dB/Sh/corintean-Ca/abacus/arch with dEnt/	2stepsplatform/dB/Sh pilaster/corinthian-Ca/abacus/arch with dEnt/dfrieze with inscriptions	Fan vault ceilings
Corner pilaster with Base dB/Sh pilaster/corintean-Ca/	Corner pilaster with Base dB/Sh pilaster/ corinthian-Ca/	springs

Legend: dB-Doric base; Sh-shaft; Sh pilaster-shaft on pilaster; Ca-capital; dEnt-Doric entablature.

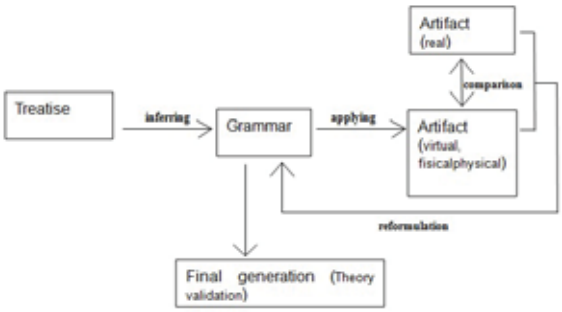

Figure 4. Flow diagram.

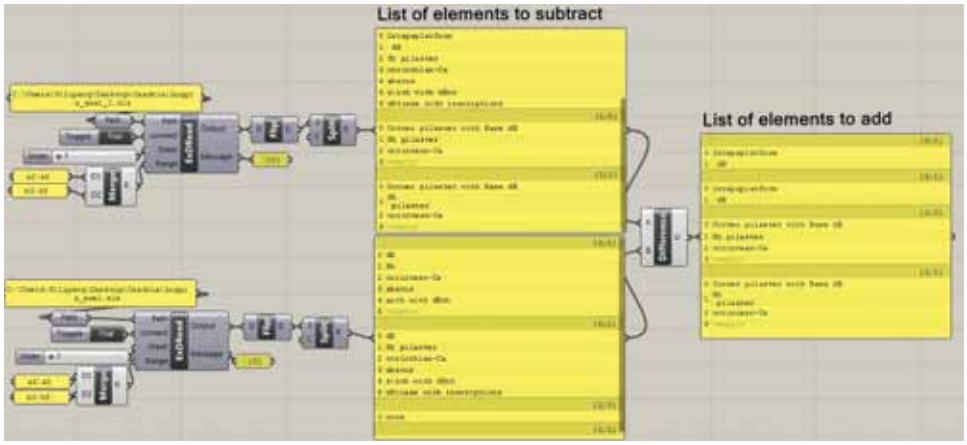

Figure 5. Comparing lists of elements to detect the ones to be added.

Figure 6. Comparing real Loggia Rucellai with its 3D model.

There was no ruled survey used for comparison in this phase of the research and it is to be said that it may contain some degree of imprecision.

Meanwhile we believe that the degree of inaccuracy does not prejudge the conclusions made because they are based on an analysis of the proportions of the column system elements (dB, Sh, Ca, dEnt, etc.). If the proportions would show large deviations among the elements, this work could not be done with this methodology and surveys would have to be carried out in the field. With this methodology (applied for this specific case) we gain some economic costs avoiding long distance travels.

4.1. RAPID PROTOTYPING

Aiming the accuracy verification of the generation, the digital model generated was printed on a 3D printer of Zcorp, a model of part of Loggia as seen in Figure 7.

This prototype helped us detect some mistakes on the positioning of the arches of the roof and how they unload in "latastrum" of the corinthian capital. There

Figure 7. Partial rapid prototype and GH code for 3D model of Loggia Rucellai.

were also other elements digitally manufactured using different techniques throughout the development of the main grammars (Coutinho et al., 2012).

5. Conclusions

The process showed in this paper is also a process of counting parts and reasoning on those parts as seen. But it also presents a method to control that information towards a deeper understanding of those parts counted.

In the derivation process there were 3 new rules added to the former grammar. Rule 8 was generated from the initial line (Rule 1) described as 3D+2wPilaster+ 3IC = L. The corner Pilaster has a width such as wPilaster = 6/5D (column diameter). Its height is hPilaster = 10+1/2wPilaster suggesting an Albertian height of corinthian column was used. Looking even closer, it's possible to verify that the Pilaster has a Doric base with ½ wPilaster and a Capital with 1 wPilaster being coincident to Alberti's prescriptions. The columns of the *Loggia* have a height (containing a latastrum) of h = 7D and the Corinthian order at *Rucellai palace* has h = 7+1/4D. Alberti's are 9D. The base is close to 3/4D (which is in the parametric variation of $1/2D \leq dB \leq 3/4D$ from the treatise). The total height of the column (the space from the floor until the arch or entablature) is accomplished by the shaft parametric variation. This transformation was occurred in stage 3 of the derivation. This may suggest that, in terms of construction, the column elements were built in the workshop and the shaft may have been the last to be cut.

The transformations found and the application of some formal elements is almost the same in the *Loggia* as in the *palace*. The corinthian capitals leafs used in the Loggia are formally similar to the ones used both in the interior palace loggia and courtyard and in the first phase of the *Rucellai palace* facade construction.

The rule 8 and 9 are new rules. If rule 8 is a parametric variation of the rules to generate a column shaft present at stage 3, rule 9 is not contained at the 7 main stages. Rule 9 regards the generation of the floor and wall within the derivation boundary. This rule generates 2 steps at *Loggia Rucellai* derivation. Due to renovation works at the palace loggia it's not possible to conclude if there is any similarity among them in this particular aspect.

It is concluded that there is an application (intentional or not) almost directly of the rules described in the treatise by the author and builder of the *Loggia Rucellai* and that some of the solutions for both buildings (*palace and Loggia*) are similar. If future applications of grammars are to generate the buildings from a target sample of historic relevance (with high probability of Alberti's influence), we may conclude that who created it had knowledge of Alberti's rules (particularly by those who traditionally are considered architects in field working close with Alberti: Matteo di'Pasti, Bernardo Rosselino and Luca Fancelli) and even some of

the builders of works in which Alberti did not participate as a designer. It might be possible to verify a pattern of design procedure. Finally, the results show that a derivation of rules may generate a 3D model very close to the real building suggesting that it is possible to generate architectural space with elements of the system of the column, i.e. the systematization of the column.

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References

Alberti, L. B.: 2011, *Da arte edificatória*, Translated by Santo, A. E., with introductory notes by Krüger, M. Calouste Gulbenkian Foundation, Lisbon.

Duarte, J. P., Krüger, M., Coutinho, F., Figueiredo, B. and Castro e Costa, E.: 2011, "Alberti Digital: Tradição e inovação na teoria e prática da arquitectura em Portugal", Presented at 2º Colóquio Internacional "Gêneses das Racionalidades Modernas – em torno de Alberti", Belo Horizonte, Brasil.

Carpo, M.: 2011, *The Alphabet and the Algorithm*, MIT Press, Cambridge, MA.

Coutinho, F., Castro e Costa, E, Duarte, J. P., and Kruger, M.: 2011, A computational interpretation of "De re aedificatoria": Translating Alberti's column system into a shape grammar, *Proceedings of eCAADe 2011*, University of Ljubljana, Faculty of Architecture (Slovenia), 788–798.

Coutinho, F., Castro e Costa, E., Duarte, J. P., and Kruger, M.: 2012, Alberti Digital – Tradição e inovação na teoria e prática da arquitectura em Portugal [Alberti Digital – Tradition and inovation in theory and practice at Portuguese architecture], *Proceedings of SIGraDi 2012*, Fortaleza, Brasil, 211–215.

Knight, T. W.: 1983, Transformations of language of design, *Environment and Planning B: Planning and Design*, **10**(2), 125–177.

Kruger, M., Duarte, J.P., and Coutinho, F.: 2011, Decoding De Re Aedificatoria: using grammars to trace Alberti's influence on Portuguese classical architecture, *Nexus Network Journal*, **13**(1), 171–182.

Kent, F. W.: 1972; The Rucellai Family and its Loggia, *Journal of the Warburg and Courtauld Institutes*, *35*, 397–401.

Preyer, A.: 1981, Giovanni Rucellai ed il suo Zimbaldone, II: A Florentine patrician and his Palace (Studies by F. W. Kent, A. Perosa, B. Preyer, P. Sanpaolesi, R. Salvini at the Warburg Institute, 24, II), University of London, London, 155–207.

Stiny, G.: 1980, Introduction to Shape and Shape Grammars, *Environment and Planning B: Planning and Design*, **7**(3), 343–352.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 801–810. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

THE EXECUTED AND THE OBSERVED IN SKETCHES: VISUAL AND COMPUTATIONAL PROCESSING FOR EXPLORATIVE DRAWINGS

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Abstract. Drawing is expressing. The mind's eye works with the drawing to materialize ideas via transforming them into visual abstractions. The genuine supremacy of drawing emerges from its potential to evoke, not from its ability to represent. Computers are harbingers of unprecedented and enriching drawing environments. Yet they also introduce ambivalences because they suppress drafter's bodily and perceptual engagement with drawings. This paper aims to delineate the similarities and differences between hand drawing and (via-computer) algorithmic drawing for design. The goal is to discuss the altering role of eyes and hands in long-contrasted virtual and material environments of drawing. The outlined comparisons of algorithmic and hand sketching should encourage research for blending digital and analogue modes of sketching.

Keywords. Drawing; computation; sketch; algorithmic; design; studio; visual; calculation.

1. Story of "Two Squares", Four and a Half Centuries Apart

The oldest preserved architectural drawings date back to the Gothic Era. Most of the drawings are generated for representative reasons, and it is hard to determine whether they were produced prior to or after construction. These drawings are not to scale, they don't feature shade and shadow, and a sense of depth is hardly perceivable. Gothic drawings highlight the vertical linearity, and are flat in nature (Branner, 1997). In some drawings buildings almost disappear under the dominantly drawn ornamental elements. However, a limited number of instructional set of drawings such as the ones included in Roriczer's *Booklet Concerning Pinnacle Correctitude,* represent different characteristics.

In the second half of the 15th century, Mathes Roriczer (aka Matthäus Roritzer), a German master builder of cathedrals, prepared a design booklet to elaborate on what he called the "proper way of designing and building pinnacles" for Gothic

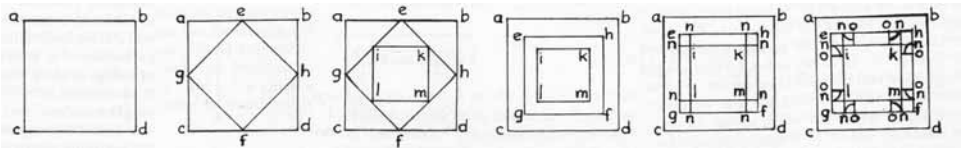

Figure 1. Roriczer's instructional drawings for development of the pinnacle base.

churches (Shelby, 1977). He claimed his book would help builders grasp the "art [architecture] they are dealing with" to overcome the flaws and imperfections of improper geometric constructions.

Throughout Roriczer's instructions for erecting a pinnacle from a base plan (Figure 1), lines are used for two different purposes: at the beginning they are utilized as guides for the descriptive geometry, such as the "base square" or the "centre line." Later they depict the outline of the (pre-conceived) pinnacle form. Regardless, Roriczer instructs the observers about what to see in his drawings. Lines and shapes, for him, are immutable entities, and their purpose is to convey a specific form: "then when you eliminate the remaining lines that are not needed for the setting out, there remains such as form as shown below."

The visual similarity between George Stiny's two squares (Figure 2) and Roriczer's pinnacle base is striking. What is more striking is the fundamental difference between the ways these two authors look at and see things. They both draw, they both look at what they draw, and although the shapes *appear* to be the *same*, they see different things. Roriczer's shape is a static entity that is not open

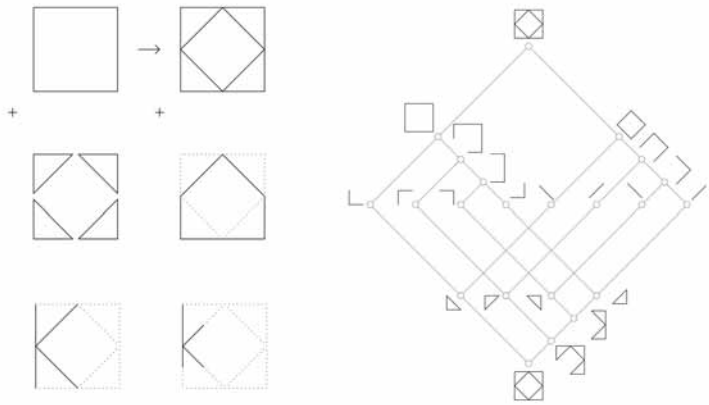

Figure 2. George Stiny's 2 Squares and their non-hierarchical network: You can see almost anything.

to interpretation, so it cannot be changed. In contrast, Stiny (2011) looks into the two squares and sees four triangles, pentagons, K's or k's, or a network of non-hierarchical shapes.

The goal here is not to compare and contrast the two sets of drawings that were produced roughly four and a half centuries apart; it is rather to emphasize the configuring power of the observer's eye in defining or deciding what a shape actually means.

2. Putting Parts Together: Hand Sketching vs. Algorithmic Sketching

While designing, the components of drawing fall into place to reveal design intentions and forms. Sketching comes into play, as the way to quickly explore, if not to document ideas. It usually employs traces that are deprived of precise geometric constructions. For R. Evans (2000): "…the sketch is without obvious geometry."

Drawing is not instant. It happens over time, and it is a product of aggregation, accumulation and omission of traces. The bits one draws merge, dissolve, overlap towards something greater than themselves. Renaissance artists are known for cultivating their drawings this way (Brothers, 2008) (Figure 3). Not the pre-conceived idea, but the visual clues discovered *in the course of drawing* embody the outcome. The parts drawn fuse together to evolve into a design-communication device: the drawing.

Visual clues can be explored computationally in the absence of the pen and paper. Once considered as a systematic whole of relational parts, a design could be explored via algorithms (Terzidis, 2006). Algorithmic thinking does not necessitate

Figure 3. Leonardo da Vinci, Study of Neptune, black chalk or charcoal, 25.2x38.9 cm.

Figure 4. Algorithmic explorations of node connectivity: Spherical Networks.

use of computers; however, they can be considered as productive collaborators because of their high capability to handle complexity.

The algorithmic study *spherical networks* (Figure 4) can represent how nodes and lines could be used to produce conceptual drawings of network connectivity. The underlying GC-Script algorithm, developed in 2005, helps visualize the rule-based relational system of nodes (points) and connecting bridges (lines). Each node in the network connects up to a certain number of neighbouring points depending on a proximal threshold. User defined parameters, such as threshold distances, can be iterated to explore various visualizations. One can start developing a *sense* of potential formal composition of the system only after sequential executions of the algorithm.

Note that the density in the spherical networks model increases towards the centre of the configuration. This is a result of the shortening corresponding distances between the points distributed on the underlying circumscribed spheres in the system. The structural density of the core, for instance, could be reduced either by decreasing the number of points per subsequent sphere surface towards the centre or by modifying the rules of proximity-dependent connectivity. In each case, the model is re-constructed from scratch.

In a way, the process becomes some sort of sketching action. An abstract formal idea, once translated into an algorithmic system, can produce sketches for visual evaluation. However, these translated algorithmic sketches cannot be altered as rapidly as hand-sketches. For instance, would it be "fair" to break a pure algorithmic system to modify only one individual member out of, say, thousands? If we *break* all the system to modify that single unit, would the drawing become "truer" (Cook, 2008)? If one does not want to disturb the algorithmic mechanism of the drawing, one could insert new sets of rules into the algorithm: a rule could be employed to modify the system for the system to become flexible enough to accommodate one or several manual (by-hand) modifications. However, in such a scenario the role of the hand would significantly differ from its role in sketching.

Algorithmic constructs necessitate translation of conceptual ideas into rule based systems via syntax, and thus an algorithmically created sketch appears not

simultaneously with, but following mental processes. In hand drawing it is hard to define how thoughts, transformations and traces occur. Both hand and (via-computer) algorithmic sketching could be accepted as feedback mechanisms; however, the differences exceed similarities.

3. What do the Computational Tools for Design do?

3.1. BINARY SYSTEMS, BRUTE FORCE AND DESIGN

Any computer application, due to the binary nature of the machine language, operates via discretization of the world. One has to subdivide things into tiny bits and re-compose (assemble) them using configuration methods to generate designs. However, design concepts that relate to aesthetics cannot necessarily be directly translated into computational means (Fishwick, 2006). Computational tools developed for designers enable computation of Vitruvius' *commodity* and *firmness* concepts more than the *delight* one.

Parametric systems assist the designer in defining explorative design domains with numeric or geometric dependencies and constraints. Parametric models require a linear bottom-up modelling process and this very nature makes them incompatible for immediate inclusion or exclusion of (geometric) parts. Moreover, because of their deterministic logic, parametric systems produce the same result when same the sets of parameters are used, in contrast to real-life dynamics.

Unlike parametric systems, systems incorporating stochastic searches (such as genetic algorithms) can utilize probability and grant designers a more open-ended design process. However, the valid designs are still determined via constraints within the definition of the problem (Pottmann and Bentley, 2007): the solution to the design problem is somehow already bounded in the domain defined by the preconceived fitness criterion.

Computational simulations help analyse probable real-life performances of designs. Although the architectural design industry uses and benefits from such tools, these tools also produce invalid results, and thus the data they produce requires insightful examination for their proper use. Non-expert users might sometimes forget that a simulation incorporates the reconstruction of conditions of reality, not the reality itself.

All the methods covered here benefit from the number-crunching ability of the computers and they mostly suppress the potential contribution of seeing.

3.2. VISUAL ENGAGEMENT AND CODE

Computers enable us to work with constructs of higher complexities which arguably cannot be laid out precisely with pen and paper. The precision required

Figure 5. Maeda's explorative sketches and final graphic design for Shiseido.

to work with computers can only be achieved after long skill-building sessions. Yet even after, the unforgiving nature of computers remains there to keep designers' ambivalent feeling towards them fresh. However, this unforgiving nature might also produce (accidental) unexpected outcomes: optimistically, one may discover something new to look at and see about what one is designing. The time invested to build an algorithmic drawing system is counter balanced with the gain of variety of the visualizations that could be extracted later on.

Ironically, such unexpected discoveries do not lie embedded in the parametric relationships of the computational system. These discoveries rather come into existence as perceptual products of vision. Eye works with the drawing the way it would work in a hand drawing: it looks and sees something beyond the computer's constructed *vision*. Arguably, for this very reason, regardless of the advancements in computing, designers keep working with both digital and analogue mediums. Designers mix and match techniques such as digital printing, hand drawing and scanning. Switching between these modes is an effort to translate the products between the two not-so-incompatible digital and analogue worlds.

Maeda's work represents this bi-modal work process. His algorithmic constructs are products of visual materials explored by the eye and the hand (Figure 5). The code comes into play to outline and then algorithmically refine the image to perfection; technology and art become counterparts (Maeda, 2000).

4. Teaching How to Design and Draw Computationally

Today, students can be accepted as the largest group of early adopters of any computational design tool. Design studios incorporating new techniques and

understandings provide environments to explore unprecedented design forms, and to experiment with new materials and digital prototyping techniques. However, conventional techniques, even at the times the studios prefer them to diminish, keep influencing the processes.

Architecture students have to discover ways of *playing* with geometry and make it their own to develop confidence for design exploration. Computers should be introduced as tools for them with which to build and look at things. A top-down teaching method, feeding the students with certain forms and modelling techniques, would only make them followers of the precedents. Likewise, not supplying enough material to play with would be discouraging. Arguably, what the students need is a safe ground on which they can feel confident enough to discover their own design *gestures* and their potential of *seeing* while utilizing computers for design exploration.

Basic Design Studio at the Istanbul Bilgi University, Department of Architecture was constituted around such an idea. The studio aimed to discover and teach ways of generative design thinking via *algorithmic constructions* and *visual evaluations*. Transformational patterning exercises proved satisfactory for these two core concentrations.

Students did an empirical exercise by drawing closed polygons and generating arrays of them via applying planar transformations. They were free to draw any closed polygon, and they could apply any type of planar transformation (translation, rotation and scaling). Three operations of polar or rectangular arraying helped them finalize their patterns. At the end of the exercise they had to discover newly emerging polygonal figures and classify them as *main shape(s), secondary shape(s), transition shape(s)* and *connector shape(s)* (Figure 6).

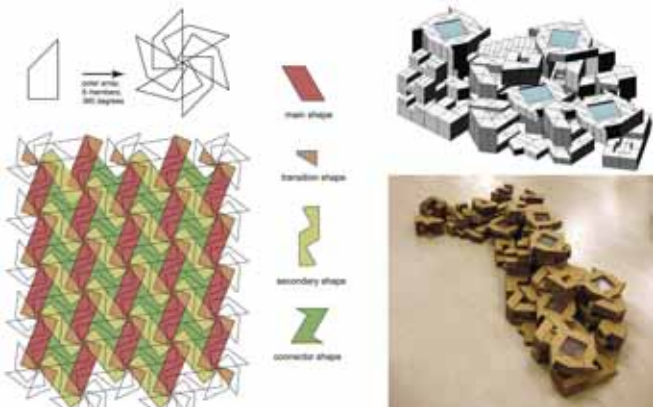

Figure 6. First year Basic Design studio: Student Beril Binoğul's pattern exercises and her 3D maze.

The emerging pattern, after their subsequent modifications, became the medium for students to look into and evaluate. They made their own discoveries through drawing, seeing, evaluating and interpreting. They modified the sequences of operations they picked to manipulate the resulting shapes they produced. These sequences were represented with an algorithm (computational calculation) and the products were evaluated visually (visual calculation).

Students had both computational and perceptual exercises to attribute meanings, functions, and even *personalities* to the figures. Such attributions helped them define and design unique parts to be composed into their own designs. The final step of the exercise was formulated around an imaginary creature made of water of a certain mass. The aim was to construct sequential voids to accommodate this creature while it navigated through the voids of a 3D maze as it changed physical phases to *fit in, flow or evaporate* (Figure 6): "…design a 3D maze in which your water creature will cycle through, in and out. Let your creature *witness* different conditions as it passes through different voids, find entries and exits throughout its life of cycles."

Practiced by students and extended to more sophisticated assignments, similar techniques enable students to work with forms and configurations of much higher complexities both in 2D and 3D exercises. In the following example, students sequentially transform polygonal units to build an intricate structurally sound adaptive bridge (Figure 7).

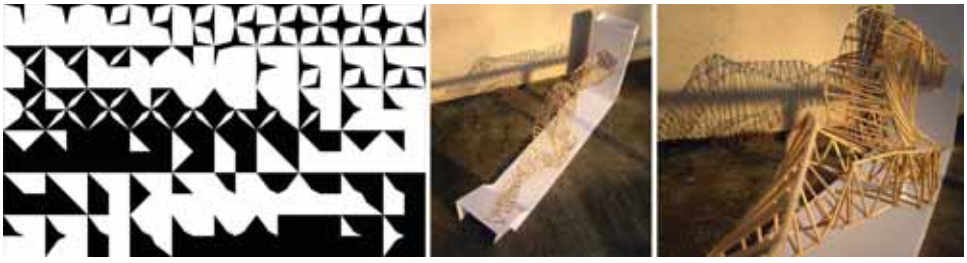

Figure 7. First year undergraduate student Ulufer Çelik's sequential transformations applied to a polygonal shape (left) and Yağız Özkan's "wall to hollow" bridge (right).

5. Contributions

5.1. ALTERNATIVE WAYS FOR VISUAL AND COMPUTATIONAL PROCESSING OF HAND-DRAWINGS

This paper is about the eye and its potential to discover hints of new designs within drawings. Computation, without a doubt introduces novel methods, mediums and

means to explore (with) design drawings. Yet the impossibility of fathoming *the emerging* is what is valuable in sketching. Zero dimensional calculation (Stiny, 2006), however, as opposed to the on-going branding about emergence in computational design, cannot fully support *the emerging*. In a sense, algorithmic sketches remain intangible and impermeable. In other words, an algorithm can *produce* sketches, yet a potential shift in intention requires a structural modification and re-execution of the code. The code may appear as a hindrance to the immediacy of the sketch. A pencil stroke proves more efficient and tactile, albeit less precise.

The outlined comparisons of algorithmic and hand sketching here do not aim to praise one of these drawing modes above the other. Rather, they aim to explore how these modes could be brought together. These comparisons should be used as a motive to search for alternative methods of sketching that could incorporate feedback mechanisms between hand, eye and the computer.

5.2. WORK IN PROGRESS

Research about incorporation of computational methodologies into drawing processes have been developing around gestural interaction and shape recognition, and are definitely re-shaping the drawing process, yet the investment in the eye and vision might potentially introduce alternative ways for novel discoveries. A hypothetical workflow that incorporates a computational camera that *looks* at one's drawing process to produce auxiliary imagery for enriching the visual clues (Figure 8) provokes an alternative way to *draw with computation*. A hybrid drawing model that

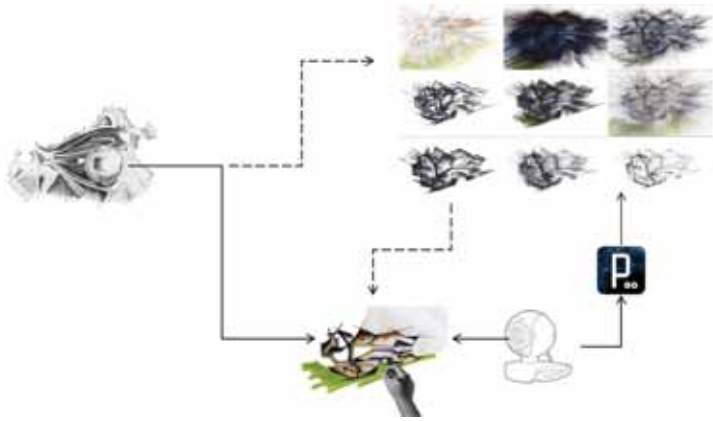

Figure 8. Eye-Camera coupling for hard-drawing. A computational camera can record the development of drawing, extract embedded but not seen drawings and apply computation to produce auxiliary drawings during the process of drawing.

merges digital and analogue methodologies, acknowledging the limitations and potentials of both will prove more tangible, accessible and enriching.

References

Branner, R.: 1997, Villard de Honnecourt, Reims, and the Origin of Gothic Architectural Drawing, *in* L. T. Courtenay (ed.), *The Engineering of Medieval Cathedrals*, Ashgate, Aldershot, UK, 63–80.
Brothers, C.: 2008, *Michelangelo, drawing, and the invention of architecture*, Yale University, New Haven.
Cook, P.: 2008, *Drawing : the motive force of architecture*, John Wiley, Chichester, UK.
Evans, R.: 2000, *The projective cast: architecture and its three geometries*, MIT, Cambridge, MA.
Fishwick, P. A. (ed.): 2006, *Aesthetic computing*, MIT, Cambridge, MA.
Maeda, J.: 2000, *Maeda@media*, Rizzoli, New York.
Pottmann, H. and Bentley, D.: 2007, *Architectural geometry*, 1st ed., Bentley Institute, Exton, PA.
Shelby, L. R.: 1977, *Gothic design techniques: the fifteenth-century design booklets of Mathes Roriczer and Hanns Schmuttermayer*, Southern Illinois University, Carbondale.
Stiny, G.: 2006, *Shape : talking about seeing and doing*, MIT, Cambridge, MA.
Stiny, G.: 2011, What Rule(s) Should I Use?, *Nexus Netw J*, **13**(1), 15-47.
Terzidis, K.: 2006, *Algorithmic architecture*, 1st ed., Architectural, Oxford.
Vitruvius, P. and Morgan, M. H.: 1960, *Vitruvius: the ten books on architecture*, Dover, New York.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 811–820. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

3 SCALES OF REPURPOSED DISPOSABILITY

Diversion of Construction, Renovation and Demolition (CRD)

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Abstract. Project managers and construction contractors have long recognized the importance of reducing waste and salvaging high value construction and demolition materials such as copper and other metals. Contractors are usually careful about the quantity of materials ordered, how materials are used and how to carefully de-construct valuable materials. In most cases however, materials that are more difficult to separate and that are worth less per unit weight are still going to landfill, even when they are present in large quantities. This represents an inefficient use of natural resources and uses up landfill capacity unnecessarily. Unfortunately, some contractors do not realize that there are new opportunities for waste minimization, while others are reluctant to implement environmental practices because they believe these practices will increase their project costs. Most contractors are concerned about the cost of the labour that is needed to deconstruct materials for reuse or recycling. However, it has been shown that effective waste management during CRD projects not only helps protect the environment, but can also generate significant economic savings. Various projects from within our practice and within our academic curriculum will be brought into the attention of this paper. Specifics of modularity, form/fit/analysis, fabrication, and off-site production, will be demonstrated within the larger discussion through the focus onto three case studies.

Keywords. Construction alternatives; waste management; offsite production; fabrication; form/fit/analysis; modularity.

1. Introduction

The premise of the paper will discuss three scaled prototypes of which utilized the idea of how repurposed waste materials are sourced within the field of architecture, and the developmental nature of the design utility based within the parameters of repurposing. The basic use of these prototypes range from 1) an

architectural modular developed as an attempt to address the issue of construction waste produced by demolished project sites for unskilled workers within developing countries, 2) an art installation piece which addresses overstocked and over-ordered materials and EPS foam, originally used for insulation, by contractors for an existing institutional construction project in Houston, Texas, and 3) an academic design-research project that was further pursued as an art installation sculpture, made for the HKSZ (Hong Kong Shen Zhen) Biennale, which uses localized wood materials, pre-fabricated through CNC, tried-and-tested to be constructed offsite, to limit the onsite production, delivery, and man-power.

Each of these projects instigate the a range of developing processes of computational design-research and the parallel intentions of diversion within the construction, repurpose and demolition processes inherit to the production of architectural design. All three case studies utilize and appropriate construction waste, and consider the repercussions of the construction waste within a novel form of fabrication and processing for the built environment. Incorporating the 3Rs (reduce, reuse and recycle) into construction, renovation and demolition waste management creates a closed-loop manufacturing and purchasing cycle. This significantly reduces the need to extract raw materials, reduces the amount of materials going to landfill sites and reduces the life-cycle costs of buildings and building materials.

2. Basis of Development

According to the *United States Environmental Protection Agency* for Region 8, the qualifying basis of construction and demolition (C&D) materials are as follows:

> Construction and demolition (C&D) materials consist of the debris generated during the construction, renovation, and demolition of buildings, roads, and bridges. C&D materials often contain bulky, heavy materials, such as concrete, wood, metals, glass, and salvaged building components. Reducing and recycling C&D materials conserves natural resources and landfill space, reduces the environmental impact of producing new materials, creates jobs, and can reduce overall building project expenses through avoided purchase/disposal costs.
>
> In recent years, numerous efforts have been underway to reduce the environmental impacts of construction and demolition projects. EPA Region 8 helps promote and facilitate the recycling and reuse of these materials by providing useful information and grants, tools, and resources. The following provides links to these resources through frequently asked questions.

Given the basis of the classification of materials which consist as construction and demolition materials, the following projects were researched and developed

according to the nature of the use and need. Most importantly, each prototype and design-research project dived into the computational aspects, in both high-tech and low-tech opportunities, and investigated the fundamental requirements, computational rigour, and intrinsic opportunistic possibilities of computational tooling in both analogue and digital testing as a means of understanding the material opportunity provided as a CRD material, while looked upon the use of the material as a hybridized retainer for the larger development of the premise.

3. Resilient Modular System (RMS)

Resilient Modular System (RMS) is a continued collaborative academic project that is working towards a regional grant approval. RMS is a multi-disciplinary research proposal to forge the synergy and efforts between three different colleges/departments within the University of Houston: College of Architecture, Department of Industrial Engineering, and Department of Material Studies and Engineering. The topics and fields of research will include, but will not be limited to: Architecture/Design, Industrial Engineering and Prototyping (Digital/Analogue), Patents, and the Material Sciences. Within the larger understanding of the design-research, all conducted research will require a high level of computational science and bio-engineering support. Each collaborator/Faculty member is a key asset to the development of this project and is experts within their respective fields.

The division of research and development will be as follows: **Prof A** (Architecture/Design/Prototyping), **Generic** graduate student (Architecture/Design/Prototyping), **Prof B** (Patent/Industrial Engineering/Modular design aspects for form and fit analysis), and **Prof C** (Material Sciences/Bio-related engineering). The developmental nature of the RMS is to design-research into a modular system that could be applied as urban interventions within the context of temporary and permanent settings (Figure 1).

Using both eco-intelligent architectural design objectives, the knowledge and technique of manipulating sustainable materials ultimately pursues a positive impact on the planet as a growth opportunity and engenders a focus on enhancing benefits (not only reducing costs) through its decision-making and actions – taking an approach of optimization rather than minimization. This Project can understand the perspective of "people, planet and profit," as expansionist and enabling leadership through the achievement of advanced success metrics. For example, the concept of effective design of products and services should move beyond typical measures of quality – cost, performance and aesthetics – to integrate and apply additional objectives addressing the environment and social responsibility.

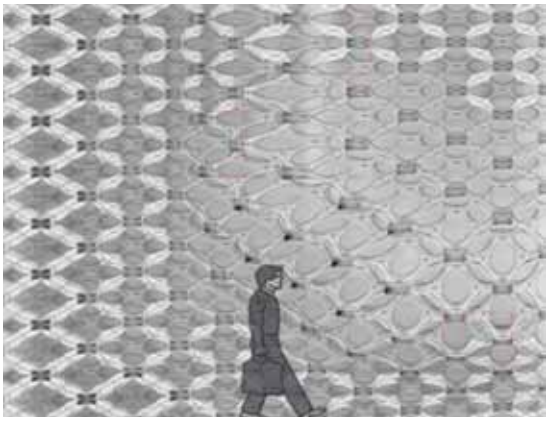

Figure 1. Scale, iteration, and tessellation of the RMS modular system.

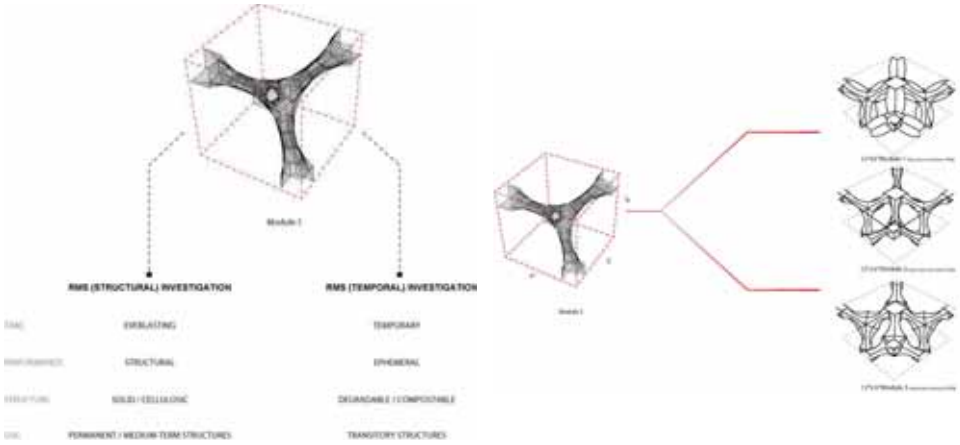

Figure 2. Dualistic research approach of RMS.

Through both digital and analogue (physical) prototyping in both architectural and design scales and migrating the opportunity of a full-cycle cradle-to-cradle design process into a Design-Fabrication project – with real-world contextual testing, and use of both repurposed construction waste and biodegradable materials (specifically, biodegradable soy-based polyurethanes, ceramic fillers, and composite plastics) – RMS (temporal + structural) is to find a dualistic opportunity into sourcing ecological solutions of constructing temporary structures within the built environment in locations of need (Figure 2).

The idea of the RMS (temporal) is the ability of it to become an ecological and resilient modular construct for the built environment that could be subsequently dissolved, yet, in an effort of full-cycle design, also contribute to nourishing the natural landscape.

The temporary proposal is that one of these structures could be possibly constructed as a retaining wall system –similar to the ones that are seen along the side of the highway or a landslide retention wall. The composite within the mixture of this will consist of ceramic filler, broken down glass, and biodegradable plastic as the main composite material. The process of this works as follows: 1) a landslide retaining wall is constructed with the RMS module, 2) due to exposure and UV tested breakdown, when the biodegradable plastic comes to the end-life, 3) the plastic will degrade and dissolve. 4) Since the plastic is made with a mixture of ceramic filler, 5) when the plastic dissolves, 6) the ceramic filler will be left, and since the ceramic filler itself retains moister, 7) when the ceramic filler is deposited into the soil, it would provide itself as a form of nourishment for plantation and development for agricultural growth.

The primary material research for the RMS (temporal), ephemeral structure, will be based on agricultural or soy-based biodegradable polymers have been in research since the late 90s and have been improved, bought out and carried forward, by some of the world's largest companies, like food and agricultural giant Cargill, who in 2008, spent over 22 million USD on developing a method to research and use polyols that can replace petroleum-based chemicals. The most effective method is to blend soy protein plastic with biodegradable polymer to form soy protein based biodegradable plastic, and forming the material with the method of extrusion and injection-molding to form useable pieces of plastic. Therefore, using the same traditional methods of constructing plastics, the same design fabricated parts would be used for applying similar 'thermoforming' or 'vacuum' forming techniques into constructing the prototypes.

While the secondary research for the RMS (structural) will be research for repurposing construction waste, as a mixture for the remediation of the structural testing and joint detailing, the same modular structure will be utilized to further the innovate on studying the structural form/fix/analysis of the RMS (structural) modular.

4. Geo-Cognition

Geo-Cognition is based on the geometric concepts of projective geometry (duality principal) and the convergence theory, and the fusion of the four main geographic locations that had the most significant impact within the artist's career and life. The supervening confluences, which occur through transitional develop-

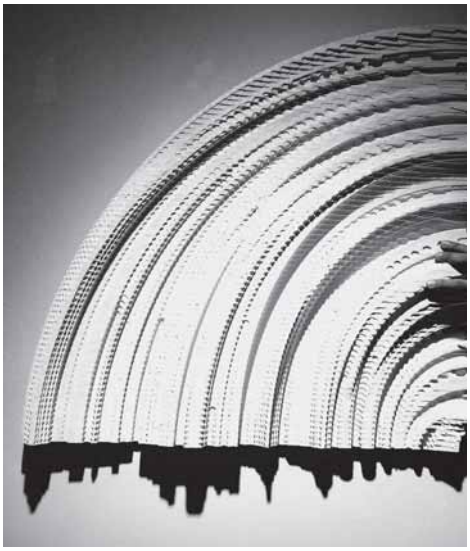

Figure 3. Singular modular example of the Geo-Cognition installation (Note: Shadows produce Cityscape).

ments between the cities, are formalized by utilizing a form of projective geometry, and attach itself within an underlying cognitive geometrics theory.

The confluences of the cities, through its linearity and dynamics, are representations of both durational and formal natures of the transitions. These factors are carefully developed and linked to the artist's respective influences and the relative time spent within the period of that city, resulting in the dynamic affects which transition between the axioms of the different skylines and planes. Formally speaking, the different skylines merge (converge) from one into another, creating a morphogenesis between the planes (Figure 3).

> Projective Geometry is the branch of geometry dealing with the properties and invariants of geometric figures under projection. In older literature, projective geometry is sometimes called 'higher geometry,' 'geometry of position,' or 'descriptive geometry' (Cremona, 1960, pp. v-vi). The most amazing result arising in projective geometry is the duality principle, which states that a duality exists between theorems such as Pascal's theorem and Brianchon's theorem, which allows one to be instantly transformed into the other. More generally, all the propositions in projective geometry occur in dual pairs, which have the property that, starting from either proposition of a pair, the other can be immediately inferred by interchanging the parts played by the words "point" and "line" ("Projective Geometry", n.d.).

The material exploration of Geo-Cognition was made possible by utilising the byproduct of an architectural construction site. Fact shows that most US construction sites and construction managers overstock on more than 30% of building materials for construction. Over 70 million tonnes (155 000 million pounds) of waste is produced in the construction industry each year. This amounts to 55 LBS per week for every person, about four times the rate of household waste production.

The EPS DOW insulation foam used to CNC mill, produce, and fabricate Geo-Cognition was made possible through donations from an actual construction site (a commercial building on the campus of the University of Houston), whereby the site manager offered us to take the overstocked material.

Through reusing the overstocked insulation material, it provided us (the artist) complimentary materials for production, while also lessening the waste creation and dumping cost for the contractor. This type of cradle to cradle/grave approach to design allows an innovation of creation, and amalgamation between art and architecture. Different material explorations, including the use of HIPS and MDF, and several prototypes were made before finalising on the EPS DOW insulation.

5. Tetra V2

Tetra V2 is an urban sculptural installation created for the HKSZ (Hong Kong Shen Zhen) Biennale 2012 that provided evidence of offsite production (4 days of CNC and production work), and less than eight (5) hours of on-site installation, with the assistance of three workers (Figure 4).

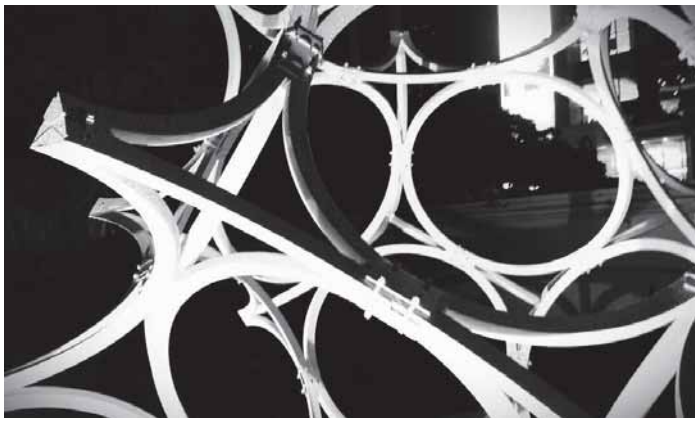

Figure 4. Onsite installation of the Tetra V2 at the HKSZ Biennale.

The intention of the Tetra V2 computational process was developed through rhino as an overall procedure to expedite the installation process by devising an off-site pre-fabrication, manufactured, and construction system, using localised and repurposed MDF materials within the region of Hong Kong. The installation was developed as an academic project at the Chinese University of Hong Kong for a summer 2011 studio, which was subsequently furthered as an installation commission for the Hong Kong Shen Zhen Biennale. The larger intention of the piece was to understand the load bearing materials of repurposed wood materials, and understanding the manufacturing process of the CNC for offsite assembly. The design of the efficiency for offsite transportability and onsite construction, therefore, became a key asset into the umbrella premise of designing the sculpture itself.

Given the minimal budget and constraints of the design itself, the continuous production of utilising the CNC in an innovative flat-cut 2-axis process, rather than the typical 3-axis production, made this structure an assembly project rather than an innovation of the tooling itself. Each arm of the tetra-pod is composed of two pieces of 2-axis flat-cut MDF, whereby each tetra-pod itself is composed of six arms, whereby each pod is comprised of twelve pieces. The ability to construct a three-dimensional structure is therefore, played into both the computational tooling of the piece, and also the innovation of the assembly.

The construction and demolition of the piece was, therefore, an innovation of repurposed materials, however, the hybridized approach of offsite assembly and onsite installation also expedited the de-installation of the structure. Whereby lead to the ease of transportability of the piece to be later become part of the permanent collection of the BGCA Foundation in Sai Kung, Hong Kong.

6. Performative Criteria

The basis of these prototypes and design-research projects are prospective projects in hopes to deliver a performative criteria and incentive to produce a continued effort into generating the material appreciation, and conscious approach to the continued discussion of generated waste production and management within the construction industry. While a large part of the debate is to better fulfil full-cycle design and cradle-to-cradle full loop development, in the case of the Resilient Modular System (RMS), the larger discussion is to provide a model of research that circumstances to allow the cradle-to-end result of construction waste to be repurposed rather than to have been disposed. All three instances functionally outsources to the utilitarian approach to further the results of the architectural state of the material, and transposes the traditional expectations of the end-result of the produced product or design – by creating a viable and creative method to the end-product.

The current environmental crisis and diminished natural resources has challenged the practice of Architecture to re-think its outdated processes of design and construction. New processes that act as full regenerative cycle systems are replacing existing wasteful construction models. The scope of this work focuses on the understanding and development of minimal surfaces specifically of those that are Triply periodic (i.e., Periodic in three direction) as an efficient modular building component fabricated out of high content recycle/salvaged construction solid waste. Each building component will be designed utilizing computational generative strategies to find the most optimal performance. Rapid prototyping and digital fabrication methods will be utilized in order to find efficient and economical modular structure systems that perform at three levels: **structurally, environmentally and socio-economically.**

7. Conclusion

The diversion of construction, renovation and demolition (CRD) waste from landfill sites is an issue that has been gaining attention within both the public and private sectors. Surveys have indicated that as much as one third of the 20 million tonnes of solid waste of municipal waste streams is generated by construction, renovation and demolition activities. Many of our landfill sites are reaching capacity. In addition, CRD waste is sometimes illegally dumped or burned, causing land, air and water pollution. The increasing costs of disposal are ultimately reflected in project costs, as contractors must incorporate anticipated disposal costs in their bid costing. Realities such as these emphasize the need for initiatives that focus on reducing and diverting as much waste as possible from CRD activities.

With the rise of computer aided technology, the vast amount of rapid prototyping tools prompts designers to question how our visions of objectivity diverge into the tendency to push and understand the limits of different material properties to further the development of architectural design. The premise of this research proposal is to achieve speculative studies within a project framework, which will be presented through a quad-fold process of: design-research, fabrication-construction, exhibition-publication, and international distribution (including patents).

Design – the larger function of the term inclusive of Research and Development of Applied Sciences, Engineering, Technology and Architecture – today could perhaps be described as the relational equations mediated by digital techniques assisted with production and knowledge of fabrication. Like many fields in the modern culture, it strives to be truly integrated wherein the designer can move seamlessly from concept to production in a single, contained process.

The much larger discussion is less of how the demolition technique is developed, however, is the greater control of the material that is processed, where with

demolished materials are reused. Part of the problematic debate within the construction, renovation and demolition argument originates from the structural integrity of reused materials, and the incentives provided by the localised governments for the repurposing of the materials. Whether computational techniques are required as a means to further the research, computation should however, be viewed as a means to test and further the potentials for opportunistic developments, rather as purely as means to digitize the technique of building.

According to the *United States Environmental Protection Agency* a large part of the initiatives for repurposing materials within the field of construction is dedicated to the reduction and reuse. Rather than looking into the means of solely researching with the on-going problems that end-materials produce, perhaps the larger research and development should be to look into potential re-establishments of the materials into cradle-to-end results, which place a larger affect – whether cultural, social, or economical – into the societies of which architecture and construction place an importance in.

Acknowledgements

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References

Baerlecken, D. and Duncan, D.: 2012, Junk – Design Build Studio, *CAADRIA 2012 – Beyond Codes and Pixels*, CAADRIA, Hong Kong, 305–313.

Bechthold, M.: 2008, *Innovative Surface Structure – Technologies and Applications*, Taylor and Francis.

Cremona, L.: 1960, *Elements of Projective Geometry*, 3rd. ed., Dover, New York.

Grobman, Y. J. and Neuman, E.: 2012, *Performalism – Form and Performance in Digital Architecture*, Routledge.

Oxman, R. and Oxman, R. (eds.): 2010, The New Structuralism: Design, Engineering and Architectural Technologies, *Architectural Design*, **80**(4).

Peinovich, E. and Fernandez, J.: 2012, *Localised Design-Manufacture for Developing Countries*, *CAADRIA 2012 – Beyond Codes and Pixels*, CAADRIA, Hong Kong, 285–294.

"Projective Geometry": n.d. Available from: Wolfram MathWorld <http://mathworld.wolfram.com/ProjectiveGeometry.html> (accessed 1 April 2013).

Sheil, B.: 2012, *Manufacturing the Bespoke: Making and Prototyping Architecture*, AD Reader, John Wiley & Sons, UK.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 821–829. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

MESH GRAMMARS

Procedural Articulation of Form

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Abstract. We introduce a formal grammar as a computational approach to the generation of design. While existing shape-grammars transform primitive shapes as lines or rectangles, the presented production system specifically addresses polyhedral objects described by three-dimensional meshes composed of vertices, edges and faces. The parameters of the transformation rules are sensitive to topological and topographical properties of the selected input mesh. We demonstrate that this approach allows the creation of new ornamental structures and can lead to a new language of architectural forms.

Keywords. Generative; procedural; subdivision; shape grammars.

1. Introduction

This paper introduces a new approach for procedural design of architectural forms and ornaments called “mesh grammars”. Using procedural design, one can generate complex shapes that cannot be drawn with an acceptable effort directly via user input. With small adjustments to the rules, a wide range of variations can be calculated in a short time.

A number of procedural modelling techniques exists to create three-dimensional models from sets of rules: L-Systems and fractals are often used to model plants or landscapes, while shape grammars have been applied on a theoretical level in the fields of art and architectural design. Despite their prevalence in academia, shape grammars have not gained a widespread relevance as a generative design tool in architectural practice. Their use has primarily been limited to analysing, encoding and re-applying existing architectural composition rules.

The motivation of our research is to develop a procedural instrument that allows design of new, complex architectural forms and novel structures of orna-

mentation. We therefore extend the possibilities of existing shape grammars with a grammar for the articulation and refinement of polygonal meshes.

This paper first gives a short overview and discussion of the related concept of shape grammars. In the second part, a formalism called "mesh grammars" is introduced. Finally, we present examples of forms generated by applying these mesh grammars, and we conclude with an outlook. In summary, this paper makes following contributions that have not been demonstrated:

- A formal grammar addressing multi-facetted mesh geometry.
- Context-sensitive parametric rules responsive to both topological and topographical attributes on a local and global level.
- Application of the mesh grammars to the generation of architectural artefacts.

2. Conceptual Similarity to Shape Grammars

Stiny and Gips (1971) introduced shape grammars as a computational technique for rule-based design. Shape grammars can be seen as the graphical correspondence of production-systems used for languages. The rules of production systems are composed of two parts: a left-hand side a sensory precondition ('if' statement), and right-hand side action ('then' statement). In shape grammars, these two parts are defined as:

- Recognition of a particular shape and selection of the corresponding transformation.
- Replacement of the shape by a new shape, transformed according to the specification of the applied rule.

Shape grammars are a useful instrument for computer-aided architectural design under formal aspects. Composition principles can be digitally encoded as rules. The combination of different rule sets enables a large variety of designs and high detailing with relatively small programming effort. Architectural shape grammars have been mostly used for analysing composition rules of built architecture (Flemming, 1987) and for the computational reproduction and recombination of existing "styles" (Duarte, 2005; Müller et al., 2006).

Despite the theoretical work on shape grammars as an analytical tool during the last thirty years, shape grammars have neither found widespread implementation as generative tool for design, nor are they documented as design method for built architecture. The potential of a rule-based procedural design as generator of new architectural forms is as of yet largely unrealized. The authors identify two broad manners in which a rule-based design tool can be extended to from an analytical tool to a generative instrument.

2.0.1. Moving from primitive shapes to polyhedral objects

As the rules of shape grammars mostly use primitive shapes as input (such as points, lines, planes and solids), the amount of implemented rules is often very high. For instance, the shape grammars used to generate floor plans of Palladian villas (Stiny and Mitchell, 1972) consist of 69 rules that are processed sequentially in eight steps.

The rules of the presented mesh grammars focus on polyhedral three-dimensional objects. These objects are described as polygonal meshes composed of connected faces, edges and nodes. The process output is not an agglomeration of isolated shapes but again a mesh, i.e. a network of connected elements.

2.0.2. Context-sensitive parametric modifications

The rules of shape grammars usually operate using affine transformation, addition, splitting, or direct replacement of shapes. When using parametric rules, these operations are adapted according to properties such as size or proportion of the input-shape.

The rules of the presented approach include vertex-based three-dimensional operations of shape-internal deformations with context-sensitive parameters. They deform the mesh at each location in a differentiated way depending on the local and global context.

2.1. THE MESH GRAMMAR PROCESS

The starting condition of the process is a polygonal mesh of any level of detail and complexity. The process itself consists of applying a rule to this mesh in order to produce an output mesh (Figure 1). This application can be repeated for a fixed number of iterations or it can continue until the mesh exhibits a specific attribute.

The rule itself has two components: an attribute of the mesh that is to be measured, as well as a mapping function that specifies how the measured value is

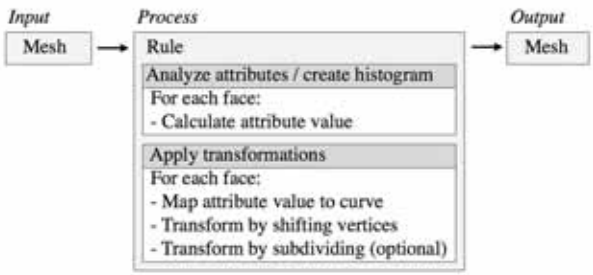

Figure 1. Mesh grammar flow chart.

converted into a transformation of the mesh. Mesh transformations consist of translation of vertices along faces' normal vectors. Optionally, transformation can include subdivision of the mesh.

2.2. MESH ATTRIBUTES

Mesh attributes are measured at the level of individual faces. They can broadly be classified as either topographical or topological, and one can distinguish between attributes that are local and can be measured using only a single face, and those that are global and measure a face attribute relative to its context (Figure 2).

The spatial distribution of any attribute can be monitored at any iteration by visualizing faces' values as a grey-scale map (Figure 3). This provides a preview of how vertices can be translated.

	Topographical	Topological
Local	• Area • Perimeter • Jaggedness • Parallelness • Planarity	• Number of neighbors • Number of vertices
Global	• Curvature • Orienation • Distance to point/ border/centroid /etc.	• Nodal distance to border • Nodal distance to corner

Figure 2. A selection of mesh attributes.

Figure 3. Attributes of a subdivided mesh visualized as shades of grey. From left to right: curvature, planarity, jaggedness, distance to initial vertex, and distance to initial edge.

2.3. MAPPING FUNCTION

The link between a measured attribute value and a translation operation is a mapping function. This function, usually in the shape of a curve, specifies how an attribute value is converted into a translation of vertices. An underlying histogram that measures the distribution of either absolute or relative (percentile) attribute values can be used to monitor and control the mapping (Figure 4). The histogram allows an easy specification of clipping values, and can provide visualization of distributions using different scales on the x-axis – such as a logarithmic scale.

Mapping functions provide control of a spatial transformation of the geometry through the use of a linear pattern. The histogram of attributes indexes the three-dimensional structure of the mesh in a linear order. By mapping this distribution of values to the parameters of the rules with various curve-functions, the resulting transformation of the mesh is manifested in three dimensions (Figure 5).

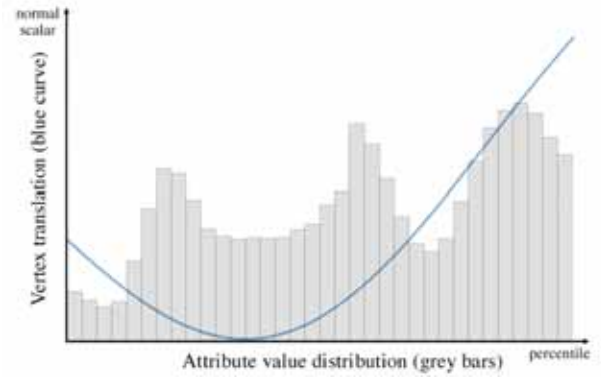

Figure 4. Mapping function with underlying histogram.

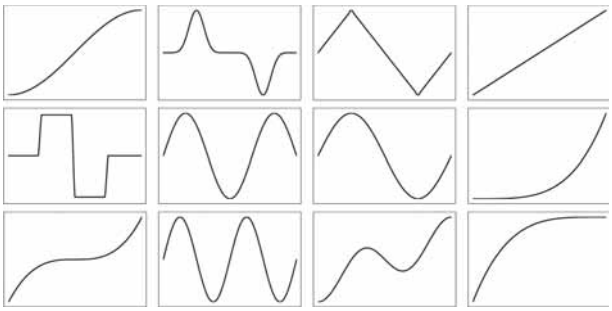

Figure 5. A selection of mapping functions.

2.4. MESH TRANSFORMATION

Mesh transformation always entails a translation of vertices to generate a new output mesh, and can optionally be accompanied by mesh subdivision.

2.4.1. Translation vectors

Vertices are translated using their normal vectors, which in turn are multiplied by a translation scalar. The translation scalar is specified by the mapping function. The unscaled extrusion vector can be calculated based on the dimensions of the face, or calculated as a unit vector that in turn can be scaled corresponding to the current iteration.

2.4.2. Mesh subdivision

Transformation can optionally entail mesh subdivision after each extrusion operation. This enables the algorithm to work at increasingly smaller scales: first iterations can control the overall form, while successive iterations affect surface development and eventually the creation of a microstructure or skin (Figure 6). By

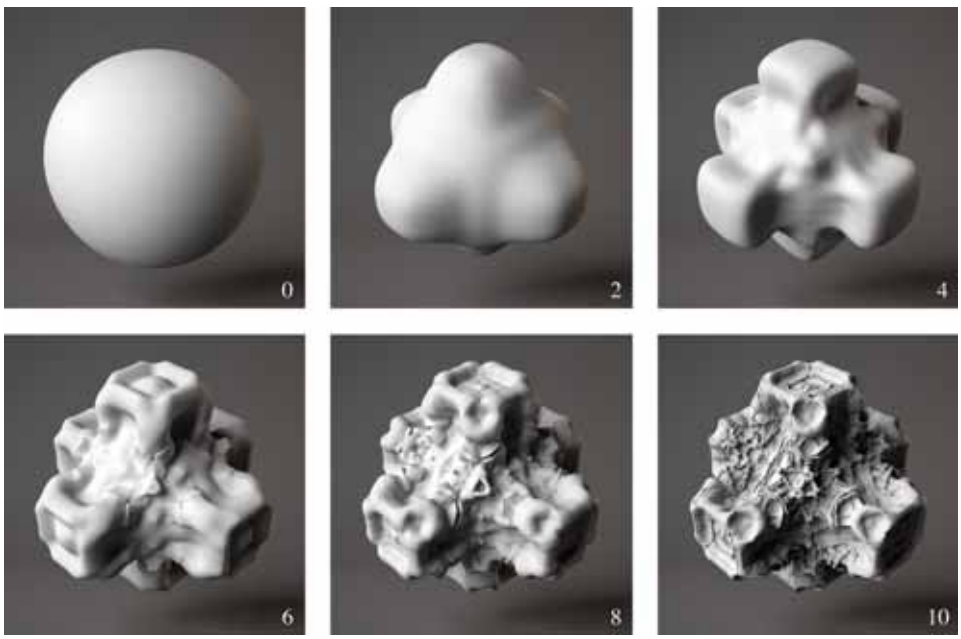

Figure 6. Successive application of a single mesh grammar rule to a sphere.

using the Catmull-Clark scheme (Catmull and Clark, 1978), for instance, it is possible to further differentiate the mesh by specifying individual extrusion factors for corner points, edge points, and midpoints of the new mesh (Hansmeyer, 2010).

3. Conclusion

3.1. SIMILARITIES AND DIFFERENCES TO SHAPE GRAMMARS

Mesh grammars can extend the range of applications of shape grammars. As a generative design tool, they provide an unseen vocabulary of forms and ornament that cannot be created using traditional design methods (Figure 7). As meshes are a generic description format of three-dimensional geometry, the presented procedural approach can easily be adapted to given architectural contexts and to different scales of architectural elements.

Although the presented process is deterministic – as the same combination of rules applied on the same mesh produces always the same result – it is difficult

Figure 7. Mesh grammars with a spherical input mesh (rendering). (Continued on next page…)

Figure 7. (Continued...)

to foresee the outcome. As attributes of one mesh always result from attributes of the preceding mesh, small changes in the weighting of parameters can propagate and lead to new and oftentimes surprising results. Thus, while the design is only truly controllable in an iterative trial-and-error process, this unpredictability offers the chance of discovering unexpected results in an open formal range.

With the inclusion of parametric rules into the grammars, local attributes of the mesh are uncovered, articulated and accentuated. Through the context-sensitivity of the transformations, the resulting structures maintain an organic connection to the input shape. The generated ornament appears to evolve out of the mesh rather than being an afterthought. Structure and ornament are fused into a single entity. Even the simplest input mesh with only a single rule can evolve into a highly articulated shape within less than 10 iterations.

3.2. OUTLOOK

The potential of mesh grammars as a generative tool for architecture could be further explored through a refinement of the presented transformation routines. This

could include, for instance, the integration of physical constraints or of geometrical constraints such as collision-detection.

It has recently become possible to materialize the forms hat this mesh grammar process can generate. The development of both subtractive and additive digital fabrication methods is happening hand-in-hand with the increase in computational power necessary to calculate high-resolution meshes. Fort he first time, geometric complexity is no longer an impediment, but in its malleability it becomes an opportunity.

References

Catmull, E. and Clark, J.: 1978, Recursively generated b-spline surfaces on arbitrary topological surfaces, *Computer Aided Design*, **10**, 350–358.

Duarte, J. P.: 2005, A discursive grammar for customizing mass housing: the case of Siza's houses at Malgueira, *Automation and Construction*, **14**(2), 265–275.

Flemming, U.: 1987, More than the sum of parts: the grammar of Queen Anne houses, *Environment and Planning B: Planning and Design*, **14**, 323–350.

Hansmeyer, M.: 2010, Subdivision beyond smoothness, *Proc. Computational Aesthetics*, London.

Müller, P., Wonka, P., Haegler, S., Ulmer, A. and Van Gool, L.: 2006, Procedural modelling of buildings, *ACM Trans. Graph.*, **25**(3), 614–623.

Stiny, G. and Gips, J.: 1972, Shape grammars and the generative specification of painting and sculpture, *Information Processing '71*, North-Holland, Amsterdam, 1460–1465.

Stiny, G. and Mitchell, W. J.: 1978, The Palladian grammar, *Environment and Planning B: Planning and Design*, **5**(1), 5–18.

DESIGN TOOL DEVELOPMENT

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UNDRAWABLE ARCHITECTURE

Digital workflows for the conservation of heritage buildings and the discovery of digital tectonic

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Abstract. This paper presents a data centric perspective to historical building conservation using digital media. In particular we explore a workflow based on large volumes digital data acquired via 3D scanning technology, virtual restoration using 3D modelling and physical artefact reconstruction using 3D printing technology. We offer an alternative perspective in contrast to the prevalent approach of reverse engineering or geometric rationalization via parametric design technology; highlight the research and design opportunities as well as the challenges of the approach.

Keywords. Digital conservation; 3D scanning; rapid prototyping.

1. Introduction

Approximately every one or two decades, historical buildings require conservation work. Unlike practices in the West (Chung, 2005) where material preservation is paramount, it is common in Asia for large parts of buildings to be periodically disassembled and reproduced. The Ise Shrine in Japan, perhaps one of the most famous examples of this tradition, is rebuilt every twenty years (Adams, 1998) while the Temple of Heaven in Beijing, a world heritage monument (UNESCO, 1998), underwent disassembly, restoration and reassembly in 1971, 1991 and 2005. The long tradition of conservation by reconstruction has both technical, as well as cultural significance: prevalent use of organic material, for example timber in contrast to masonry, paired with the regional climatic conditions means that historical structures require regular maintenance and replacement of damaged building components. By coincidence or necessity the process is also aligned with a very different philosophical understanding of historical value (Wells, 2007) which does not primarily interface with material and form but rather time and place.

Figure 1. Top: The Yueh Hai Ching temple in Singapore prior to 2011 restoration, Bottom: Damaged gold gilded timber ornamental bracket being replicated on site by craftsman.

Reconstruction does not merely preserve the physical embodiment of historical artefacts but also the artisan processes and technics of their creation (Figure 1).

Introducing digital methods in a domain we characterize as the realm of undrawable architecture is fascinating in as much as challenging. Undrawable architecture underpins a process of tacit tectonic knowledge passed along generations which was never formalized, and a product of artisan craftwork of phenomenal complexity that was manually re-produced but never rationalized. While it is possible to geometrically model historical artefacts using conventional computer aided design methods it is foreseeable how impractical an enterprise as such may be. Conventional digital methods and tools adhere to a reductionist paradigm: we use computer models as accurate yet coarse but nevertheless effective abstractions of reality. We work analytically using Cartesian constructs but we are aware that we can only physically construct approximations thereof. This is not a property of digital media but rather relevant to the notion of rationality or modernity in design (Alexander, 1964). However when confronted with artefacts governed by radically different regimes of thought and modes of production we may naturally raise questions on the efficacy of rational methods: it is perhaps no longer only a question of feasibility, whether or not we can effectively reverse engineer craftwork, but also one of whether it fundamentally makes sense to do so. The end results of analytical modelling would also have been most likely problematic as for instance specifying building works via linearized representations of physical artefacts that contain not even a single straight line, hints not only of the difficulties with the process but also those of the products.

Instead, we approached digital conservation from a data oriented perspective, operating on large sets of raw information produced and processed by scanning, computing and prototyping technologies. The decision for taking a hyper-realist approach, that is a paradigm where the more data the merrier, offers us an opportunity to examine an alternative mode of digital praxis where focus is shifted away from expressing and retaining well-defined explicit relational design states of geometry to an arena of big data and flows.

The proliferation of scanning and visualization technologies during the past two decades has expanded the scope of cultural heritage to realm of Virtual Heritage which broadened the discourse of the experience and interpretation of culture places and artefacts (Affleck and Kvan, 2005; Rahaman and Tan, 2009). The recent introduction of digital fabrication technologies in architecture (Schodek et al., 2004; Kolarevic and Klinger, 2008) has the potential of enriching the discourse through the study of the physical dimension of cultural heritage which we attribute as the digital heritage tectonics. The notion of digital tectonics, a methodology of integrating design software with traditional construction methods, (Beesley and Seebohm, 2000) is extended here by establishing conduits between prior and posterior physical conditions via digital sensing, processing and making. We are interested in the implications of digital prototyping and fabrication of historical artefacts as they offer the ground for technological research as well as philosophical debate: Can we foresee future replacement of historical artefacts by digital prototypes? What if we record and digitally reproduce crafting processes, not merely forms, by CNC machines? We note that when reconstruction is integral to conservation, due to practical urgent reasons for doing so, it is critical to accept and embrace the importance of reinterpretation. Reinterpretation in almost certainly unavoidable as building components are recreated by different craftsmen using affine techniques and based on partial remains or photographic evidence. Questions of authenticity have been and are still extensively debated by international heritage conservation organizations such as ICOMOS and UNESCO (Lemaire and Stovel, 1994; Engelhardt and Rogers, 2005). In this respect our effort cannot aim at efficient reproduction of frozen-in-time artefacts but extends to contributing to the debate of reinterpretation and fostering knowledge acquisition through observing and making experiences of architectural heritage.

In this paper we focus on the development of a workflow from scanning-to-fabrication. We present the opportunities and challenges of digital conservation through the case study of an on-going historical building restoration program; namely, the Yueh Hai Ching temple situated at the centre of Singapore's business district. The extant building, built between 1895 and 1896, is being restored since 2011 having last undergone a program of conservation in 1996. Our paper offers a starting point for practitioners and educators in design technology and historical

building conservation sharing a critical assessment of means and ends analysis of relevant CAD methods.

2. Relevant Work

Architectural conservation of built heritage overlaps with engineering, topography, archaeology, and computer science. Reverse engineering and redesign is relevant in the reproduction of objects by analysis of physical artefacts as well as in process-knowledge acquisition, which may lead to future design improvements (Otto and Wood, 2000).

Reverse engineering methods, such as shape rationalization, using geometric fitting, are employed for the reproduction of industrial design objects which are the result of already rational geometry and manufacturing methods. In this respect, archaeology is certainly closer to heritage conservation in the nature of the evidence under study as its artefacts are results of traditional arts and crafts. Topography and land survey offer precursors of contemporary data acquisition methods such as terrestrial scanning instruments descend from topographic survey techniques (Bohler, 2006; Georgopoulos et al., 2009). Computer graphics made impact in heritage conservation by the introduction of technologies for the study of heritage with focus on the visual aspects of the objects under investigation. Geometric surface reconstruction (Hoppe et al., 1992), point set registration (Desl and McKey, 1992) and visualization of large data sets (Gobbetti and Marton, 2004) have been extensively investigated during the past decades. Notably the Digital Michelangelo Project (Levoy, 1992) offers a pioneering study of 3D sensing technologies for the geometric reconstruction of historical artwork. Architecture has a long tradition of historical study and building conservation and has followed closely the advancements of digital design technologies. Notable as well as one of the early examples of digital conservation is the study of the Segrada Familia Cathedral by Mark Burry investigating the tectonic dimensions of Antoni Gaudi's architecture using parametric technologies (Burry, 1992).

Our study is situated at the intersection of architectural history and architectural computation in the light of by-now widely available mass sensing, parallel computing and rapid prototyping technologies. Digital tectonic also denotes an interest in the discovery of the interplay between material, form and the formation process in historical architectural artefacts.

3. Workflow

The conventional workflow of building conservation involves efforts in archival research, documentation and planning. Construction entails a process of careful

Figure 2. Diagram of macro-scale workflow augmentation opportunities and micro-scale workflow actions from scanning, to digital processing and physical or visual prototyping.

disassembly, analysis and evaluation of damages, reproduction of components and final reassembly. As traditional crafts are fading due to modernity certain building parts are often shipped to China where they are recreated from fragments and/or alternatively craftsmen travel on site for extended periods of time. Our workflow will inevitably replace, while not substitute, this process. For the time being we aim at augmenting conservation practices by easing documentation and planning at the front-end, while potentially assisting in end-production, for instance shipping replicas in their original condition instead of damaged components. Our workflow is comprised of three segments: (a) Acquisition of data, (c) Computer modelling and (c) Digital fabrication and rapid prototyping (Figure 2).

Architectural artefacts span a wide range of scales, from hundreds of meters to fractions of a millimetre. Unfortunately, there exists no technology capable of addressing the entire range without shortcomings (Boehler and Marbs, 2002). We thus defined multiple levels of resolution (Guidi et al., 2009) for data acquisition: Building Scale: using long-range terrestrial light detection and ranging technology (LIDAR), generating registered point-clouds, and Component Scale: using near-range structured light equipment generating photo texture mapped meshes.

Our attempts to operate on massive data sets using architectural computer aided design software was utterly unsuccessful because they were not designed for

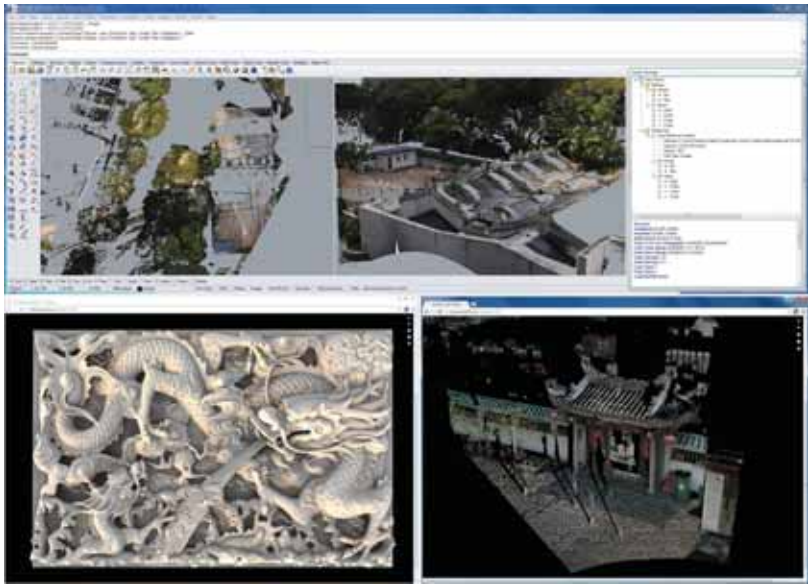

Figure 3. Left: Digital Heritage (alpha) extension for Rhinoceros 3D CAD. Right: online point cloud and mesh web-application viewer available at: http://ds1.jeneratiff.com.

such purposes in terms of both memory management and available editing tools. Instead we used a range of specialty commercial, open source and in-house developed tools. At the point of publication we are the alpha stages in the development of "Digital Heritage", an extension of a commercial CAD application (Figure 3) to mitigate the aforementioned obstacles and enable architectural historians and domain experts to access the data under a familiar computing environment. We are able to load very large sets by employing view optimizations, we offer selection filters to clean up point clouds, prototyping tools for producing 3D printing ready files and exporting methods for storing data in optimized format for offline and online applications. Digital Heritage also includes a web application viewer, using experimental graphics acceleration technology and dynamically loads point cloud and meshes via progressive streaming of compressed geometry.

Given the convoluted workflow requiring investment in know-how, labor-time and expenditures in computing and scanning power, a reasonable question arises as per the cost-benefit of digital conservation. These concerns are valid but we should expect that, if technology advances at the current rate, software and hardware will become affordable in terms of cost and learning effort. However the inquiry as per what can we really do to demonstrate the unique capabilities in big-data in contrast to conventional reverse engineering rationalization is a research

question. Our notion of undrawable architecture raises a question about production: within our industrial manufacturing regimes of production undrawable also means un-reproducible as no conventional fabrication method can effectively substitute craftwork without rationalization and/or the offsetting premise of mass-production. However, digital methods of production can exactly fit in those constraints. Our proposition is simple: we can bridge directly between computer sensing to digital manufacture letting digital input talk to digital output. Scanners, desktop computers, 3D printers or CNC machines are oblivious to the volume of information but more sensitive to format. We thus have an uncanny circumstance where historical craft meets contemporary mass-customization.

4. The Dragon Wall

We investigated the feasibility of 3D printing for real scale artifact reproduction. The granite dragon carving mounted on the wall of the Yueh Hai Ching temple during its last restoration program in 1996 was removed in order to restore the wall to its original ceramic shards ornamentation. This provided the research team the opportunity to carry out trial experiments without the need to take precautionary measures necessary with historic artefacts. Geometrically the wall is highly complex featuring deeply concave and undercut surfaces with impressive fine details given its extremely hard material (Figure 4). Scanning required only a half-day session producing circa 10GB of data. Processing amounted to a week's effort generating geometry at various resolutions: 3 million polygons per square metre for archival, 700 thousand for fabrication / prototyping, and 64 thousand for visualization (Figure 4).

We targeted plaster powder 3D printing for post-processing workability even though our polymer printer produced more accurate and durable parts. As the wall

Figure 4. Left: Granite dragon wall carving removed from the Yueh Hai Ching temple. Right: high-resolution mesh geometry generated by structured light 3D scanning technology.

Figure 5. Left: Dragon-scale-one prototype. Right: snapshot of the assembly process.

dimensions exceed the printer's build volume we segmented the model into 3D tiles and embedded fixing sockets in order to prop the dragon off a planar substrate. 71 tiles were produced in a 30-day period of 20-hour printing cycles; each print contained two to three parts. Cyanoacrylate adhesives were used to reinforce the weak plaster material and allow the supporting props to thread directly into the printed sockets. Post-processing and assembly required three weeks of work (Figure 5).

We produced a fairly impressive one-to-one replica (1.7x1.2x0.2m) of the original solid granite wall in an almost egg-shell thin structure (3mm) with minimum material use and weight (50Kg). We feel that the emergence of a hybrid material grain merging hints of the original stone carving tool, traces of mesh triangulation and the layered 3D printing process presents an interesting perspective towards re-interpretative reproduction. Interestingly, our assumptions about prototyping material weakness were unfounded. The final plaster-CA composite was surprisingly resilient to the degree that we could have produced a self-supporting thin-skin wall without additional supports. The printing technology used produced dimensional errors both after printing and in excess after infiltration due to chemical thermal expansions. Additional finishing was required to mitigate visible errors. Printing time was the bottleneck in the process and with currently available technology the only way forward is performing segmentation optimization for minimizing effective print volumes. The approximate cost for the wall was circa 6,000 SGD which while it is not dismissible it is also not unreasonable given the size and complexity of the prototype.

5. Conclusions

In conclusion we presented an outline for a digital workflow with big-data for architectural historical conservation with focus on digital fabrication. Our study

offers an overview and highlights potential and challenges involved. As we are building methods and techniques from the ground up, we are still at early stages in the discovery of the digital tectonic: the core principles of the arts and craft in heritage buildings. Our future goal is to understand the interplay of individual parts and the whole, the structural and material domain of historical buildings and the reproduction of carpentry and masonry components using CNC technology. Moreover as part of our curriculum we plan to offer join courses between architectural history and technology were students will have the opportunity to engage with architectural heritage through both literature review but also hands-on experiences with digital recording and fabrication.

Insofar, lessons learned from historical building conservation and digital design methodology we observe there is a different kind of architectural complexity contrasting historical and contemporary form. While our digital techniques are flexible, expressive and forgiving, their results are relatively straight forward, predictable and thoroughly rational. After-all, the genotype of digital form is an excruciatingly descriptive process which invariably surfaces into the object itself. This is unlike historical form, which while it is governed by principle, its formal expression is artisanal, improvisational and less divisible due perhaps to the stronger bonds between geometry, material and craft. It is arguable to what degree those processes and products are relevant in contemporary design praxis, however the progressively shorter spans between design and production via digital fabrication brings interesting potential for the near future. In one or two decades when 3D scanning will be performed using mobile phones and prototypes may be 3D print at home it is also arguable that we will think and make the same way we are today.

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References

Adams, C.: 1998, Japan's Ise Shrine and Its Thirteen-Hundred-Year-Old Reconstruction Tradition, *Journal of Architectural Education*, *John Wiley & Sons*, **52**(1), 49–60.

Affleck, J. and Kvan, T.: 2005, Reinterpreting Virtual Heritage, *Proceedings of Computer Aided Architectural Design Research in Asia*, New Delhi, 169–178.

Alexander, C.: 1964, *Notes on the Synthesis of Form*, Harvard University Press, Cambridge, MA and London, UK.

Beesley, P. and Seebohm, T.: 2000, Digital Tectonic Design, *Proceedings of Education and research in Computer Aided Architectural Design in Europe*, Weimar, 287–290.

Boehler, W. and Marbs, A: 2002, 3D Scanning Instruments, *Proceedings of the CIPA WG 6 International Workshop on Scanning for Cultural Heritage Recordings*, Corfu, Greece, 7–11.

Boehler, W.: 2006, Comparison of 3D laser scanning and other 3D measurement techniques, *in* M. Baltsavias, A. Gruen, L. van Gool and M. Pateraki (eds.), *Recording, Modeling and Visualization of Cultural Heritage*, Taylor & Francis, 89–99.

Burry, M.: 1992, *Expiatory Church of the Sagrada Família: Antoni Gaudí, Architecture in detail*, Phaidon Press, London.

Chung, S. J.: 2005, East Asian values in historic conservation, *Journal of Architectural Conservation*, **11**(1), 55–70.

Desl, J. P. and McKey, D. N.: 1992, A Method for Registering of 3D Shapes, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, **14**(2), 239–256.

Engelhardt, A. R. and Rogers, R. P.: 2005, Hoi An Protocols For Best Conservation Practice in Asia, *Professional Guidelines for Assuring and Preserving the Authenticity of Heritage Sites in the Context of the Cultures of Asia*, UNESCO Bangkok.

Georgopoulos, A., Ioannidis, Ch., Chrysostomou, Ch., Ioakim, S., Shieittanis, N., Ioannides, M.: 2009, Contemporary Digital Methods for the Geometric Documentation of Churches in Cyprus, *International Journal of Architectural Computing*, **7**(1), 21–37.

Gobbetti, E. and Marton, F.: 2004, Layered Point Clouds, *Journal Computers and Graphics*, *Pergamon Press*, **28**(6), 815–826.

Guidi, G., Remondino, F., Russo, M., Menna, F., Rizzi, A., Ercoli, S., 2009: A multi-resolution methodology for the 3D modeling of large and complex archaeological areas, *International Journal of Architectural Computing*, *Multi Science*, **7**(1), 40–55.

Hoppe, H., DeRose, T., Duchamp, T., McDonanld, J. and Stuetzle, W.: 1992, Surface Reconstruction from Unorganized Points, *Siggraph*, 71–78.

Kolarevic, B. and Klinger, K.: 2008, *Manufacturing Material Effects, Rethinking Design and Making in Architecture*, Routledge, New York.

Lemaire, R. and Stovel, H. (eds): 1994: The Nara Document on Authenticity, *Conference on Authenticity in Relation to the World Heritage Convention*, International Council on Monuments and Sites, Nara., Available from: < http://www.icomos.org/charters/nara-e.pdf > (accessed 6 March 2013).

Levoy, M.: 1992, "The Digital Michelangelo Project". Available from: <http://graphics.stanford.edu/projects/mic> (accessed 14 November 2012).

Otto, K. and Wood, K.: 2000, *Product Design: Techniques in Reverse Engineering and New Product Development*, Prentice Hall.

Rahaman, H. and Tan, B-K.: 2009, Interpreting Digital Heritage: A Conceptual Model with End-Users' Perspective, *International Journal of Architectural Computing*, **9**(1), 99–113.

Schodek, D., Bechthold, M., Griggs, K. J. and Kao, K.: 2004, *Digital Design and Manufacturing: CAD/CAM Applications in Architecture and Design*, Wiley & Sons, New Jersey.

UNESCO: 1998, "WHC Nomination Document: Temple of Heaven: An Imperial Sacrificial Altar in Beijing". Available from: <http://whc.unesco.org/uploads/nominations/881.pdf> (accessed 14 November 2012).

Wells J. C.: 2007, The Plurality of Truth in Culture, Context, and Heritage: A (mostly) Post-Structuralist Analysis of Urban Conservation Charters, *City & Time*, **3**(2). Available from: <http://www.ceci-br.org/novo/revista/docs2008/CT-2008-103.pdf> (accessed 14 November 2012).

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 843–852. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

STATICALLY MOTIVATED FORMFINDING BASED ON EXTENDED GRAPHICAL STATICS (EGS)

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Abstract. In the 19th century it was common to use graphical methods for study the relationship between form and force. The central element of all drawing methods for representing the inner flow of forces was the investigation of the dependence of equilibrium and force polygons, as well as their representation in two geometrically dependent diagrams with different units. This research is part of an on going project to extend the methods of 'graphical statics' of Carl Culmann (1866) to the third dimension in order to overcome some of the 2D-limitations of this approach. It is focused on the construction of resulting force within 3D and the utilization within discrete space frames (tetrahedrons) in equilibrium. The objective of the EGS is to focus on constructing in contrast to calculating. That means that the logic of the inner force flow leads to a process-oriented and visible approach of design, which gets computationally accessible. With the use of digital tools and increasing importance of performative methods of form-finding a renewed interest in these vector-based geometric methods of construction of force flow has occurred. This maybe will give the possibility to get an alternative to the common form finding methods by relaxation processes and analysis by FEM.

Keywords. Graphical statics; 3D equilibrium; form finding method.

1. Introduction

Through the expansion of graphical methods of construction of force-flow into the third dimension, the foundation for a design methodology can be laid where architecture and engineering enter into an active and visual dialog. This is also the motivation for an on going research into a visual language for the flow of forces whose roots are to be found in the 'graphic statics' developed in the 19th century by Karl Culmann (Mauerer, 1998).

Because architects primarily think and communicate by using diagrams, sketches and plans it is obvious, that drawing is the language of architects. The

same is true for engineers. From this it is clear that 'graphic statics' (Culmann, 1866), as a method for the direct visual representation of the inner distribution of forces, is predestined to promote dialog between engineers and architects. This approach will help to bring the linked professions together (Shea and Cagan, 1999) and not to emphasise the different point of view.

This is all the more valid since three-dimensional visualization is perfectly feasible using new CAD programs and so the method that was so far only used in 2D can intuitively be expanded to 3D. The first applications in this direction are already available for supporting frameworks subject to pure tensile and compression loading (Kilian and Ochsendorf, 2005), and through them the experimental and elaborate design methods of Antonio Gaudi (Huerta, 2006), Heinz Isler or Frei Otto become accessible for the drafting process. By developing the usability of the method by implementing into CAD programs a synthetic – instead of an analytic – design process can get started.

The EGS has the potential to get a very powerful tool for understanding the inner force flow, especially in the field of free-form design. It is very important to mention, that the method does not present an overly simplified view of interrelationships. It is mathematically precise and meets the standards of engineering sciences. This method of structural analysis fosters a holistic understanding of the interaction of form and structure, in other words the understanding of the internal forces within a built structure that help determine its form.

2. History

The central element of all drawing methods for representing the inner flow of forces is the investigation of the dependence of equilibrium and force polygons, as well as their representation in two geometrically dependent diagrams with different units. Such a description of equilibrium and force polygons is already found e.g. in Varignon's (1725) work 'Nouvelle Méchanique ou Statique' published in 1725. For this research the most important roots are the projective correlation of the equilibrium and force polygon, which were mathematically investigated by Culmann (1866) as 'graphic statics' based on the 'newer geometry' of Poncelet (1822) or Staudt's (1847) 'Geometrie der Lage' published in 1847. Maxwell (1864) proved almost simultaneously 'that for non-central force systems two reciprocal figures arise if and only if one figure can be considered a projection of a polyhedron' (Kurrer, 2002). However, through the development of faster computing tools and the scientific processes (Westermann, 2010) of the dawning 20th century, the graphical methods and their enormous potential as intuitive tools fell into oblivion, displaced more and more by analytical methods. Nowadays 'graphic statics' plays only more of a subordinate role in engineering practice and has

almost completely been displaced by analytical statics since the latter is more conducive to numerical analysis and therefore to calculations.

It must be recognized that all drawing methods known thus far for calculating the inner flow of forces operate in two-dimensional space. Even in the most recent research such as the 'Thrust Network Analysis' of Block (2009) investigations are carried out on a projection, which is why the subject matter deals with planar, and are just valid for compression or tension only structures.

3. Extension of Graphical Statics

3.1. NUMBER OF RESULTANTS

Planar force configurations can be consolidated into one equivalent force, of the resultant R, where an equivalent force is a force, which produces the same reaction forces as the sum of all individual forces using any static system. Different methods were developed for this purpose. The equilibrium polygon method deserves special mention in this connection. It allows the combination of a finite number of intersecting forces and a finite number of parallel and/or intersecting forces into one resultant in two-dimensional space. Intersecting or parallel forces can be consolidated into one resultant even in three-dimensional space by linking coplanar cases. On the other hand, it is not clear how skew forces can be combined graphically.

3.2. GENERIC CASE: SKEW FORCES

For a skew and thus generic force configuration in R^3 it should therefore be shown that it can be consolidated into a force pair (from many possible force pairs) through complete induction. This force pair is called (R_1, R_2). What is true here as well is that an equivalent force pair using any static system brings about the same reaction forces as the sum of all individual forces. Without loss of generality, the following conditions must apply to three forces F_1, F_2, F_3 in general position:

1. All three forces = 0
2. All three forces by pair are not in a plane
3. In the form diagram:

$$\left[\left(\vec{a}+\vec{f_1}'\right)\times\vec{f_1}'+\left(\vec{c}+\vec{f_2}'\right)\times\vec{f_2}'+\left(\vec{e}+\vec{f_3}'\right)\times\vec{f_3}'\right]-$$
$$\left[\left(\vec{t}+\vec{r_1}'\right)\times\vec{r_1}'+\left(\vec{v}+\vec{r_2}'\right)\times\vec{r_2}'\right]=0$$

$$\left[\left(\vec{t}+\vec{r_1}'\right)\times\vec{r_1}'+\left(\vec{v}+\vec{r_2}'\right)\times\vec{r_2}'\right]-\left[\left(\vec{t}+\vec{r_I}'\right)\times\vec{r_I}'+\left(\vec{v}+\vec{r_{II}}'\right)\times\vec{r_{II}}'\right]=0$$

possible pair of forces additional, possible pair of forces

4. In the force diagram:

$$\|\vec{f_1}'+\vec{f_2}'+\vec{f_3}'\|-\|\vec{r_1}'+\vec{r_2}'=0\|$$

$$\|\vec{r_1}'+\vec{r_2}'\| \quad - \quad \|\vec{r_I}'+\vec{r_{II}}'\|=0$$

possible pair of forces additional, possible pair of forces

For the initialization there are three forces F_1, F_2, and F_3 in whose action lines *g, h* and *i* are skewed against each other and whose direction and position are determined by two points each. *A* is freely chosen as the source of the coordinate system. Analogous to two-dimensional graphic statics, a three-dimensional force diagram is developed whose source is freely selectable. It is obvious, that a straight line *s* can be found, that intersects all three action lines *g, h* and *i*. So it is possible to generate two planes E_{jh} and E_{ni} which are intersecting in *s* (Figure 1).

By splitting F_2 and F_3 in two directions and F_1 in three directions it is possible to figure out the point *T* which is one point on the action of R_1. Because of the order of F_1, F_2, and F_3 in the force diagram, it is in the generic case not possible to split the whole force F_3 into the two directions. That means that a remainder of the force F_3 is R_2.

It is clear that the construction described creates only one of the infinite number of force pairs. Just like in the equilibrium polygon method it is completely

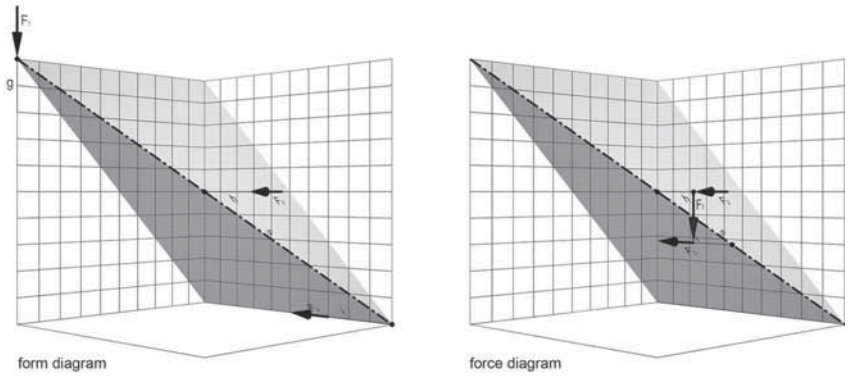

Figure 1. Intersecting lines.

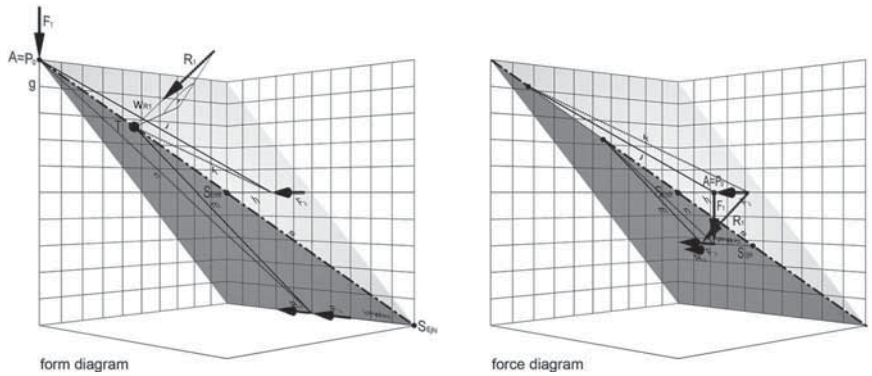

Figure 2. Three skew forces subdivided into R_1 *and* R_2.

irrelevant (cf. pitch) in which action line and at which point on the action line the construction is started but the geometric relationships of the form diagram must be transferred to the force diagram. In this respect the construction can be executed so that the remaining force lies on the action line of F_1, F_2 or F_3 (Figure 2).

In an iterative process three skew forces combined into one force pair can be linked to another force and so a finite number of skew forces can be reduced to one force pair through complete induction. This force pair corresponds in intensity and direction to the sum of all forces.

$$(F_1 + F_2 + F_3 + F_4 + \ldots + F_n) - (R_{1,} + R_2) = 0$$

and

$$(R_1, R_2) \quad - \quad (R_I, R_{II}) = 0$$

possible pair of forces additional, possible pair of forces

4. Digital Approach

The extension of graphical statics will only be fully effective if the interrelationships between form and force will be visually comprehensible even in 3D and facilitates analysis as well as an active and synthetic design process.

4.1. SELECTION OF THE CAD ENVIRONMENT

Rhinocerus 3d® offers the possibility to act very intuitive and visually in an interactive 3D environment. For many designers and architects it is common to use this

digital tool. The same applies to Grasshopper® that allows generative modelling by implement parametric elements without having a deep knowledge of programming and scripting. Because Rhinocerus 3d® and Grasshopper® are common tools in the architectural world they were chosen. It is obvious, that the standard functions of Grasshopper® would lead to a complex control diagram. However, that's why it is appropriate to implement a small Python® script. It is clear, that this implementation makes it not longer to a pure geometric calculation but rather to an algebraic method, but the user logic is still geometric and that allows a geometric and out of it synthetic approach.

As shown in section 3, any configuration of skew forces can be consolidated into two equivalent forces. This pair of forces – using any statically determined system – brings about the same reaction forces as the sum of all individual forces. The challenge is to find a simple way to start the described iterative process, especially because in every step of iteration the degrees of freedom have to be eliminated by decisions of the user. It is clear, that it would be possible to use a randomizer for doing this as well. But this depends on the use of the result.

4.2. INITIALIZATION

The first step is to initialize the system in the form diagram. To get the straight-line equation of the lines of action of the different forces it is necessary to know two points on each line of action. Out of this the relevant unit vector can be determined (Figure 3).

In the force diagram the unit vectors must be multiplied scalarly. This can be achieved easily using a slider in Grasshopper® (Figure 4). For beginning a random starting point *ak* has to be set.

Analogous to two-dimensional graphic statics, a three-dimensional force diagram is developed whose source is freely selectable. After A has been set as the source in the form diagram, it also makes sense to define $ak = P'_0$. The order of

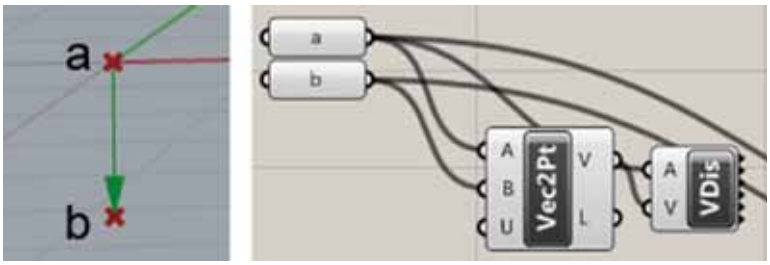

Figure 3. Initialization by using 'getPoint-' and 'Vec2Pt-function'.

Figure 4. Scaling by using a 'slider'.

force vectors f_1', f_2' and f_3' can be any but one must make allowances for the order in the following construction.

4.3. IMPLEMENTATION

All the steps of the construction described in 3 can be easy and in time calculated by a small Python® script. The construction creates only one of the infinite numbers of force pairs. Just like in the equilibrium polygon method it is completely irrelevant in which action line and at which point on the action line the construction is started but the geometric relationships of the form diagram must be transferred to the force diagram (Figure 5).

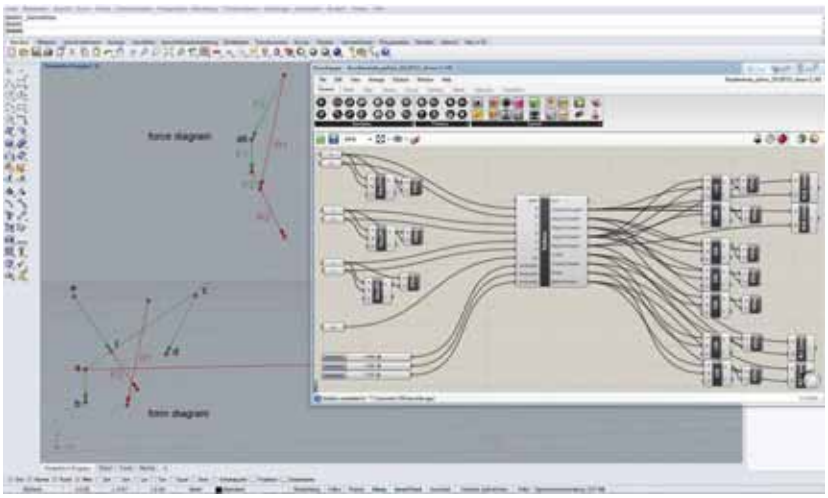

Figure 5. Full control panel with three forces.

4.4. COMPLETE INDUCTION

In an iterative process three skew forces combined into one force pair can be linked to another force and so a finite number of skew forces can be reduced to one force pair through complete induction. This force pair corresponds in intensity and direction to the sum of all forces

4.5. ADVANTAGES OF PARAMETRIZATION

The interactive and linked diagrams are offering – in combination with the Grasshopper®-Python® surface – the possibility to adjust the resultant in any direction by changing either the position of the lines of action or by an adaptation of the intensity of the forces. The adaption can be taken so far, that the constellation and intensity of the forces can be consolidated into one force instead of a force pair. In many chases wee geometrical operations simplify the force flow enormous.

4.6. SUPPORT FORCES CALCULATED BY SUPERPOSITION

First it is necessary to define any three supports. For a statically determined system in space one support has to force reactions in one direction, the second in two directions and the third has to be fixed. Now the support forces out of and can be determined using superposition. For that the simplest way is to work with tetrahedrons. For as well as for a tetrahedron between any point on the action line – except the intersecting point on the plane between the supports – has to be build. By solving graphically the support forces out of and and a subsequent superposition the support forces are determined. Out of this information it is possible to fix the closing plane – instead of a closing string in 2D – in the force diagram (Figure 6).

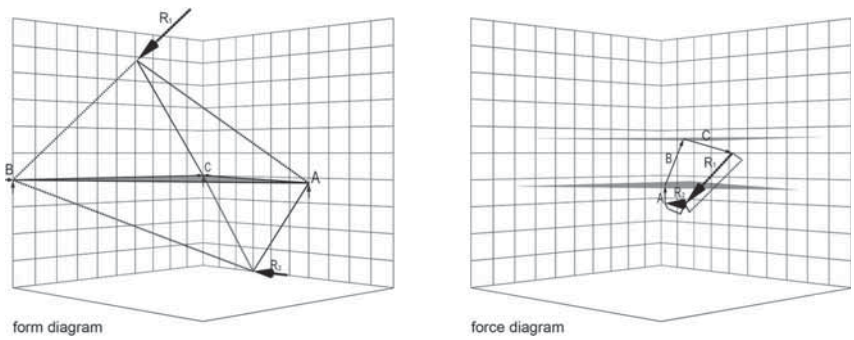

Figure 6. Tetrahedron construction for calculating the support forces.

5. Discussion

5.1. COMPARISON WITH EXISTING METHODS

Nowadays it is common to use relaxation methods for form finding and FEM for analysis. It is obvious, that both methods have their strengths and weaknesses. FEM is a sophisticated tool to allow analysis of an already designed form, but gives no direct indication how to adapt the form to get a better inner force flow. On the other hand relaxation processes are providing the possibility to optimize a rough form but just in a way of optimization. Both is only partially helpful for designing a specific form.

Because EGS is purely geometric and free of auxiliary quantities such as moments – which are used by analytic methods – it allows a resultant consideration based on geometric dependencies (e.g. diversions) and thus shows the relationship of force and form directly. When shifting forces in 3D in analytical-numerical statics, the consideration of the force pair, consisting of the resultant force and the resultant moment, is the significant component in the analysis. This type of consideration, always requires a shifting of the resultant force into a freely selectable reference point, which by definition determines the resultant moment. However, since a skew force pair arises in the generic case, the reference point is often chosen so that a force skew and thus a colinear position of the resultant force vector and of the resultant moment vector are set. Basically 'every force system can be reduced in an infinite number of ways to two forces skewed against each other, the so-called force cross' (Szabo, 1975). This is precisely what is being done in the EGS construction in just with the geometric dependency with the difference, that the result can be visually traced.

As EGS is free of material behaviours and just based on geometrical dependency, it helps to practice form finding without numerical detours. This will help to design free form, lightweight or kinematic structures in a synthetic instead of 'trail and error' process.

5.2. EXPERMINENTAL DESIGNS AT ETH ZURICH

In the 2nd year course of structural design of Department of Architecture the EGS tool have been applied. Students analyzed the 3D equilibrium by using a simple combination out of tetrahedrons. This space frame is a determinate system and the inner force flow can be easy understood with the spatial force diagram. By studying the form and controlling the inner forces, it was possible to figure out a specific form, what was neither an optimization of the forces nor a pure result of a design idea (Figure 7).

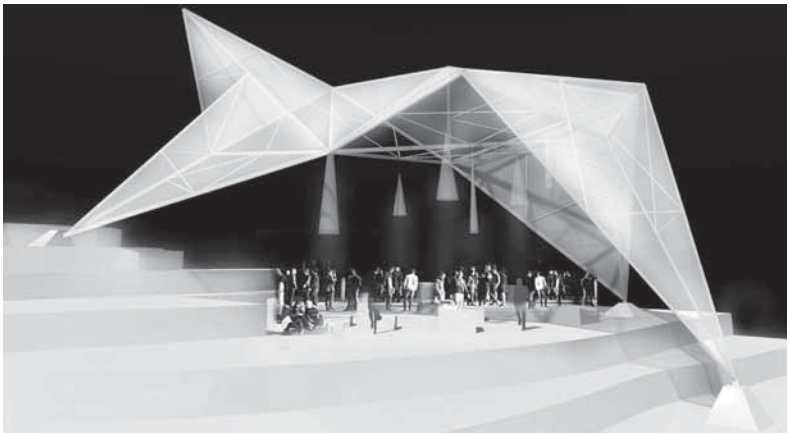

Figure 7. Student project using EGS.

6. Conclusion

By developing this method there will be an alternative to the common FEM programs. Of course the EGS will not be the sole 'miracle subsidy cure' to solve existing problems, but it will be the logical evolution of the 'graphical statics', which has been the theoretical principle of outstanding buildings.

References

Block, P.: 2003, *Thrust Network Analysis – Exploring Three-dimensional Equilibirium*, Princeton University, Princeton, NJ.

Culmann, K.: 1866, *Die graphische Statik*, Meyer und Zeller, Zürich.

Huerta, S.: 2006, Structural design in the work of Gaudi, *Architectural Science Review*, **49**(4), 324–339.

Kilian, A. and Ochsendorf, J.: 2005, Particle-spring systems for structural form finding, *IASS Journal*, **46**(2), 77–84.

Kurrer, K.-E.: 2002, *Geschichte der Baustatik*, Ernst und Sohn, Berlin.

Mauerer, B.: 1998, *Karl Culmann und die graphische Statik*, Verlag für Geschichte in Wissenschaft und Technik, Berlin.

Poncelet, J.-V.: 1822, *Traité des propriétés projectives des figures*, Paris.

Shea, K. and Cagan, J.: The design of novel roof trusses with shape annealing: assessing the ability of a computational method in aiding structural designers with varying design intent, *Design Studies*, **20**(1), 3–23.

Staudt, K.: 1847, *Geometrie der Lage*. Nürnberg.

Szabo, I.: 1975, *Einführung in die technische Mechanik*, Springer, Berlin.

Varignon, P.: 1725, *Nouvelle méchanique ou statique*, C. Jombert, Paris.

Westermann, A.: 2010, "Mathematik zwischen Leitdisziplin und Hilfswissenschaften". Available from: <http://www.ethistory.ethz.ch/besichtigungen/touren/vitrinen/studieren/vitrine23/> (accessed 20 November 2012).

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THE CREATIVE VALUE OF BAD IDEAS

A computational model of creative ideation

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Abstract. This paper analyses two ideation principles: idea accessibility and idea connectivity. Access refers to the likelihood to generate a particular idea or set of ideas for a given design task. Connectivity refers to the likelihood of one idea leading to other ideas. These principles are evaluated through a computational model. The results suggest new metrics to assess the value of new ideas. Evaluating new ideas by their accessibility and connectivity has the potential to transform current idea generation practice and research.

Keywords. Design creativity; ideation; computational creativity.

1. Introduction

Creative design ideation is the process of generating new ideas that are ultimately perceived to solve a problem or improve a situation. Novelty, utility and surprise are broadly considered as necessary conditions (Runco and Pritzker, 2011), but to generate inventive, valuable and surprising ideas is not easy. Many ideation methods focus on maximising the number of ideas, called ideational fluency. Most techniques specifically separate generation from evaluation (Osborn, 1963). This is captured by Linus Pauling's phrase: "The best way to get good ideas is to get lots of ideas". This paper examines alternative approaches to such *brute-force* approach to creative ideation. It focuses on intrinsic characterisations of the

landscape of ideas generated. A computational model is presented to provide general insights for future research and practice.

Many formal studies of creative ideation measure the total number of ideas produced by individuals or teams, and the average quality of such ideas as judged by experts (Runco and Pritzker, 2011). Some researchers have suggested that creativity research ought to study processes that maximize the quality of one or a very small number of great ideas. A result of one single breakthrough idea and half a dozen low quality ideas is preferable to a dozen of merely decent ideas (Girotra et al., 2010). In ideation research the latter would be judged as more creative as it produces both more ideas and a higher average score. Quality variance of a set of new ideas may be a more accurate and meaningful creative index (Gero and Gomez, 2009).

This paper considers two ideation principles: idea accessibility and idea connectivity, and explores their relevance through a computational model. Access refers to the likelihood to generate a particular idea or set of ideas for a given design task. This is customarily determined when repeatedly running a creative design task in similar conditions: participants tend to generate ideas following a skewed probability distribution. High accessibility indicates commonplace ideas, whilst low accessibility denotes original ideas. Conformity metrics (Genco et al., 2012) and design fixation (Gero, 2011) further provide support for idea accessibility.

Idea connectivity refers to the likelihood of one idea leading to other ideas. This is a more abstract construct based on a structural view of the idea space (i.e., fitness landscapes or network linkages). Priming effects further provide support for idea connectivity (Friedman et al., 2003). The model discussed here supports idea accessibility and idea connectivity as cross-domain heuristics that can guide idea generation independent from the design task or domain at hand.

Exploration and exploitation are ideation strategies specified in this model: the former uses random search while the latter derives rules from recent solutions in order to guide the search (Lazer and Friedman, 2007). In creativity, the structure of an idea space emerges from exploitation, i.e., rules generalised from recent solutions become source concepts leading to further solutions. This has been described in the literature as chains, streams or trains of thought. The topology of the idea space in this model can be shaped by inferred evaluation functions of interest. Ideation strategies to combine exploration and exploitation in a computational model can be predefined by the researcher, or monitoring methods can be incorporated; for example, as a function of the rate of new ideas within a recent time period.

We distinguish ideas according to their potential to generate new ideas. As a result, bad ideas (according to task performance) have the potential to become instrumental in the generation of creative ideas.

2. Computational Models of Creativity

The systemic character of creativity can be observed by the range of disciplines concerned with its study: neural, psychological, cognitive, social, linguistic, historical and management research programs (Runco and Pritzker, 2011). Computational creativity has the potential to capture the emergence of creativity from interactions at multiple levels (Sosa and Gero, 2013). Two main approaches have been adopted in computational creativity: firstly, systems that seek to model creative processes or seek to generate creative products. Generative models include those based on or inspired by human creativity, and those that aim to artificially produce solutions considered as creative by a panel of judges, audiences or critics.

The second and lesser explored approach to computational creativity consists of systems that seek to inform and inspire by enabling the systematic study of principles, factors, scenarios and interactions that assist in developing an understanding of what creativity is (Maher, 2012; Indurkhya, 2012). The systematic study of these systems helps to clarify and question assumptions, reveal insights, test hypotheses and in general help our thinking about creativity and potentially inspire innovative research and practice.

Systems built to yield products considered as creative by human judges irrespective of the generative processes, adopt a "strong" view of artificial creativity. Systems built to simulate generative and evaluative factors of creative products irrespective of the external validation of the products' creativeness, adopt a "weak" view (Searle, 1980). This measure of strength is a continuous range, rather than a discrete categorisation.

Stronger approaches address questions such as "Can computers ever be creative?", while weaker approaches consider questions such as "Can computation help us understand creativity?". These approaches complement each other. Models that aim to help us understand creativity principles inform and are informed by models that aim to mimic and transcend human creativity. The contributions of all types of computational creativity can equally inform other research traditions, for instance by framing new hypotheses, testing the consistency and implications of assumptions, and proposing new experimental settings. In-vivo and in-vitro methods can complement and be complemented by in-silico studies of creativity (Wiltschnig and Onarheim, 2010).

A semantic network study relates the creativity score of design ideas to the structure of the thinking space (Yamamoto et al., 2009). In that study, a thinking space is represented as a network with nodes as the concepts evoked in concept generation and links as their semantic relationships as defined by a lexical database. The findings include a correlation between the evaluated originality of ideas

and two features of the thinking space: mean degree or number of links and network density. A related early neural model of idea generation represents concepts in associative hierarchies where semantic entities interact in the presence of external cues (Marupaka et al., 2012). Such models based on functional neurocognitive networks explicitly represent creative ideation as "a function of how knowledge is organised". That certain thinking patterns can lead to creative ideas is a promising finding when concepts are represented by words, and provides guidance for our model of design ideation.

A complementary modelling approach has explored the connection between the creativity score of ideas and the structure of the social networks of individuals (Björk and Magnusson, 2009). They indicate a direct relationship between network connectivity and the quality of creative ideas. Similarly, Baer (2010) reports a personality dimension (openness to experience) as a moderator of the link between creativity and social network features including size, strength and diversity.

A comprehensive computational study of creative ideation could potentially combine the models described before in a tripartite system of neural networks, social networks, and idea networks. To this end, the idea-agent-social context (IAS) framework of computational creativity provides a modelling platform that includes design ideas (I), thinking mechanisms of individual agents (A), and the social context (S) (Sosa et al., 2009).

Recessive genes in genetic algorithms are building blocks in poor performing solutions that can later recombine to produce high performing solutions. The following section presents a simple computational simulation model of creative ideation. This is followed by preliminary results and a discussion of future work.

3. Modelling Ideation

The computational model of ideation described here is formulated based on the idea-agent-social context (IAS) framework (Sosa et al., 2009). In this paper we present and discuss the creative task model at the idea level (I) and leave aside individual cognitive agency (A) and the social context (S). The task used in our model can be described as a simple visual challenge as follows: "Use *g* geometries of *s* sides as the initial elements to generate as many different compositions (*g's'*) of more than *g* geometries of equal or more *s* sides". Graphically, Figure 1 depicts an example of 2 initial geometries of 3 sides (*2g3s*) that overlap to generate 3 new geometries of 3, 4 and 6 sides. Following a shape algebra notation (Stiny, 2008), a sample composition of shapes A and B includes all addition and subtraction operators, namely:

$$(g_1, g_2) \rightarrow (g_1 - g_2, g_1 + g_2, g_2 - g_1) \quad (1)$$

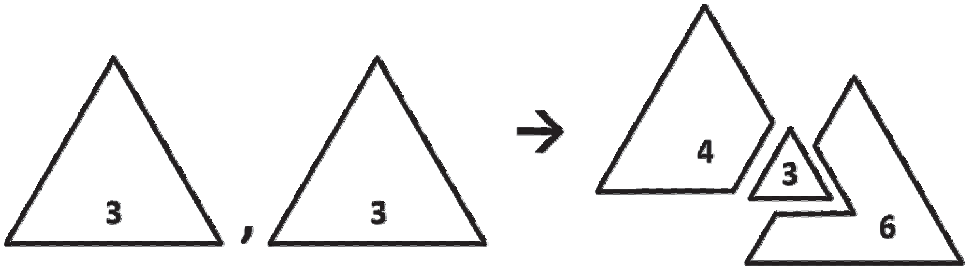

Figure 1. Two three-sided geometries (2g3s) generate three geometries of 4, 3 and 6 sides.

Figure 2. Five sample compositions from an initial set 2g3s and their notations.

In order to capture geometrical and topological relationships in this task, the following notation is used to represent shape compositions: $\{\Sigma g', i, o, l, v, (s'_1 \ldots s'_n)\}$ where: g' = final geometries, i = points located inside the area of an initial geometry, o = points located outside the area of an initial geometry, l = points located within a line of an initial geometry, and v = points located within a vertex of an initial geometry; $(s'_1 \ldots s'_n)$ is a subset of size $\Sigma g'$ that indicates the number of sides for every final geometry g'. Figure 2 depicts sample final compositions and their notations.

This visual divergence task is straightforward to represent computationally and demonstrates some elementary aspects of the ill-structured and open-ended character of design problems (Goel, 1995). It supports emergence since new shape semantics are not explicitly represented at input time (Gero and Jun, 1998; Gross, 2001). Finally, the task supports re-interpretation and learning since the final solutions can be used as input geometries or the goals can evolve over time to satisfy target geometrical or topological target features as the result of individual agency (A) or social conditions (S) (Sosa et al., 2009).

Exploration in this model of idea generation consists of defining random points in a given coordinate space from which initial shapes are built. Resulting candidate combinations are validated by criteria such as the presence of line intersections that cause shape emergence, and number of resulting shapes equal or

greater than number of initial shapes. We hypothesise that some human subjects adopt exploration at least as an initial strategy for this type of visual tasks, however this paper only represents the ideation task and not the cognitive mechanisms of ideation. The following sample cases illustrate the range of ideational fluency (mean number of ideas) in exploration: *2g3s*: 10^3 steps = 7.23 solutions; *2g3s*: 10^4 steps = 9.38; *2g3s*: 10^5 steps = 15.35; *3g3s*: 10^4 steps = 134.22 solutions. Cases are normalised over 100 simulations.

There are no intrinsic evaluation criteria in this task beyond divergence, i.e., maximising number and variance of solutions. Further evaluation functions that capture domain-specific processes can be incorporated. For example, researchers may select specific geometrical or topological relationships, or visual semantic denotations. A characteristic of creative tasks is that such evaluation functions are likely to change over time (Goel, 1995). This model captures the notion that bad ideas at time t_i may become even worse at time t_{i+1}, and they may turn into good –even great– ideas at t_{i+n} as a result of the co-evolutionary nature of design problems and solutions (Maher and Poon, 1996). These changes of target features can originate from any IAS dimension: perceptual differences or preference drift in the agent architecture (A), evolving consumer patterns or influence channels (S), technological evolution (I), etc (Gero and Kannengiesser, 2009).

Accessibility in this model is given by the mean frequency of solutions found in exploration over repeated cases. Since one of the main goals in creative ideation is to reveal uncommon yet useful ideas, in this model, ideas of low accessibility that still satisfy the task's goal can be considered as preferred over ideas that are commonly found across simulation runs. The accessibility distribution in idea spaces, r, can be characterised by $r = d_b/d_t$, where d_b represents the mean accessibility of the bottom decile and d_t stands for the mean accessibility of the top decile. When $r = 1.0$, the idea space has a uniform accessibility distribution, whilst as r approaches 0, variance increases indicating that a few 'gems' are found in a 'dense haystack'.

Exploitation in this model consists of a guided search informed by rules inferred from experience. Since time is a constraint in creative ideation, case *2g3s* in 10^4 iterations is considered in this paper. This particular choice of settings is not significant here –we plan to validate this model against human performance in this type of tasks in the future. The assumption behind exploitation as a complement to exploration is that agents are likely to develop generative heuristics as they progress in the task.

Design concepts in this model stand for generalised rules drawn from previous solutions that are used to guide the search. The rate of exploration/exploitation, defined as e, is the ratio of the total simulation steps that are spent in exploration/exploitation strategies. An e value of 25/75 means that in 25% of the

simulation exploration is active, while the remaining 75% is spent in exploitation. In case *2g3s* in 10^4 iterations, e = 25/75 generates an increase of over 90% in ideational fluency over exploration-only runs (Sosa and Gero, 2012). Although the numerical values obtained from such cases are not transferable beyond this model, in principle the significant advantage of such combinations of explore/exploit processes could imply that creative tasks (ill-structured, open ended, NP complete) are highly sensitive to ideation management strategies such as facilitation and priming.

Idea connectivity is modelled here by tracing how design concepts lead to new solutions during exploitation. Connectivity variance appears to be an important measure; in particular, what task conditions generate either solutions that lead to many solutions or solutions that are "dead ends".

4. Results: Ideas of Low Accessibility and High Connectivity

The first outcome analysed here refers to the settings of our model that influence accessibility results. Task conditions such as the size of the coordinate space influence accessibility distributions in exploration since some solutions become unreachable or less likely as a function of grid size. Likewise, accessibility distributions vary as a function of the initial settings –for example, in *2g4s*, the probability of shared vertex is significantly higher than in *2g3s*. The first principle of ideation that can be observed in this model is that the representation and the initial conditions of the task determine what can be considered the *potential creativity* of a task. The choice of representation has been shown to influence the type and degree of creativity, for example when designers choose either to sketch or to build models of their early ideas (Acuña and Sosa, 2010). More research is necessary to better understand the impact of problem formulation in creativity.

Secondly, the exploration/exploitation rate, e, determines accessibility distributions in this model. With e ranges of high ideational fluency such as e = 25/75, accessibility distributions are also the highest. As the numerator increases in e, the accessibility distribution, r, increases until a point where longer exploration periods bring about high redundancy. Such diminishing returns effects are explained by the observation that in cases where exploration is active for long periods, every idea generated has a low probability of being new. This grounds the effectiveness of e values such as 25/75 in this model: such combinations generate the highest number of total ideas because they yield higher idea variances upon which exploitation builds on novel ideas. We conclude that high productivity in exploitation requires a sufficiently large idea base that is also as diverse as possible. Combinatorial or derivative processes in ideation are more efficient when they act upon a highly diverse population of initial ideas. Future creativity research could

reveal the impact of anticipating and delaying concept variation during an idea generation session.

Thirdly, the *fertility* of new ideas can be established by the accessibility of the ideas to which they are connected. On the one hand, some solutions of low-accessibility end up leading to solutions of high-accessibility. Such rare yet redundant ideas can be understood as a "difficult way to reach easy ideas". However, other low-accessibility solutions do lead to new solutions of low accessibility too. These are very valuable in ideation as they represent "uncommon ideas that yield other uncommon ideas". For example, if in our model two inter-connected ideas require each an average of 4,500 steps to be reached, an ideation agent would only require 4,500+1 steps to reach both, as opposed to 9,000 steps if they had to be reached independently. Fertile ideas need not be of low accessibility, some high accessibility ideas (commonplace) can be connected to low accessibility ideas. These represent the holy grail of ideation: "easy shortcuts to reach rare ideas". Creativity research has yet to address the formation of chains or trains of ideas. Understanding how new ideas lead to further ideas either by 'piggy-backing' or 'leap-frogging' could yield facilitation heuristics and tools to improve collaborative ideation.

Finally, some bad ideas can be very valuable for creative ideation. In our model this is the case of low-score or even invalid solutions which nonetheless lead to valuable and uncommon solutions via a small variation. For example, solution {2,1,3,2,0 (3,6)} depicted in Figure 3a would receive a very low creativity score if the task's goal was to find 3 or more final geometries, or if the goal was to find shapes of 5 sides. Nonetheless, solution {2,1,3,2,0 (3,6)} leads directly to solution {4,1,3,2,0 (3,3,4,5)} depicted in Figure 3b through a variation in the location of a single point. The resulting solution has a very low accessibility score (0.06%) in our model, yet it would receive a very high creativity score under the aforementioned criteria since it contains 4 final geometries, one of which has 5 sides. In these conditions, solution {2,1,3,2,0 (3,6)} is a clear example of the creative value of bad ideas.

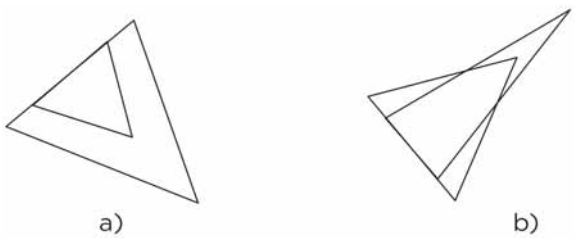

Figure 3. a) solution {2,1,3,2,0 (3,6)} and b) solution {4,1,3,2,0 (3,3,4,5)}.

5. Discussion

The modelling effort presented in this paper suggests an insightful addition to Linus Pauling's phrase: "The best way to get good ideas is to get lots of ideas" – with the addendum: "And the best way to get lots of ideas is to first generate a few that are as different as possible and then strategically build on them". This work shows the need for research in facilitation techniques that monitor idea accessibility (or any similar variance metric). The estimated accessibility distribution of the idea space can be used to balance exploration and exploitation in ideation. The estimated connectivity of solutions can be used to inform the exploitation strategies.

We are currently using this idea generation model to build multi-agent simulation models that include individual agency and social factors using the IAS framework of creativity (Sosa et al., 2009). With accessibility and connectivity mapped in a range of cases, we plan to implement ideation agents capable of self-regulating their exploration and exploitation processes. We also plan to seed the system with a few solutions of low accessibility in order to increase the generation of creative solutions. Further, we plan to validate this ideation model using human performance benchmarks to characterise the more realistic settings in our model. In such experiments, we plan to prime human subjects with fertile ideas to test whether they generate solutions of higher variance and quality.

This work aims to inform and inspire ideation researchers and practitioners. A new generation of creativity techniques could be derived from this type of work. For example, the model presented in this paper suggests that new metrics of ideation are necessary to assess the value of new ideas based on their potential to trigger more ideas, beyond their perceived value according to the task goals.

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References

Acuña, A. and Sosa, R.: 2010, The complementary role of representations in design creativity: sketches and models, *Design Creativity 2010*, Springer, 265–270.

Baer, M.: 2010, The strength-of-weak-ties perspective on creativity: A comprehensive examination and extension, *Journal of Applied Psychology* **95**(3), 592–601.

Björk, J. and Magnusson, M.: 2009, Where do good innovation ideas come from? Exploring the influence of network connectivity on innovation idea quality, *Journal of Product Innovation Management* **26**(6), 662–670.

Friedman, R. S., Fishbach, A., Förster, J. and Werth, L.: 2003, Attentional priming effects on creativity, *Creativity Research Journal*, **15**(2-3), 277–286.

Genco, N., Hölttä-Otto, K. and Seepersad, C. C.: 2012, An experimental investigation of the innovation capabilities of undergraduate engineering students, *Journal of Engineering Education*, 60–81.

Gero, J. S.: 2011, Fixation and commitment while designing and its measurement, *Journal of Creative Behavior,* **45**(2), 108–115.

Gero, J. S. and Gomez, A.: 2009, Exploring knowledge transfer in a society of designers, *in* M. Noell Bergendahl, M. Grimheden, L. Leifer, P. Skogstad and P. Badke-Schaub (eds.), *Design Information and Knowledge*, Design Society, 99–110.

Gero, J. S. and Jun, H.: 1998, Emergence of shape semantics of architectural shapes, *Environment and Planning B: Planning and Design,* **25**(4), 577–600.

Gero, J. S. and Kannengiesser, U.: 2009, Understanding innovation as a change of value systems, *in* R. Tan, G. Gao and N. Leon (eds.), *Growth and Development of Computer-Aided Innovation*, Springer, 249–257.

Girotra, K., Terwiesch, C. and Ulrich, K. T.: 2010, Idea generation and the quality of the best idea, *Management Science*, **56**(4), 591–605.

Goel, V.: 1995, *Sketches of thought*, The MIT Press, Cambridge, MA.

Gross, M. D.: 2001, Emergence in a recognition based drawing interface, *in* J. S. Gero and T. Purcell (eds.), *Visual and Spatial Reasoning II*, Sydney Australia, 51–65.

Indurkhya, B.: 2012, Whence is creativity? *International Conference on Computational Creativity*, 62–67.

Lazer, D. and Friedman, A.: 2007, The network structure of exploration and exploitation, *Administrative Science Quarterly*, **52**(4), 667–694.

Maher, M. L. and Poon, J.: 1996, Modeling design exploration as co-evolution, *Computer-Aided Civil and Infrastructure Engineering*, **11**(3), 195–209.

Maher, M. L. and Fisher, D. H.: 2012, Using AI to evaluate creative designs, *International Conference on Creative Design*, 45–54.

Marupaka, N., Iyer, L. R. and Minai, A. A.: 2012, Connectivity and thought: The influence of semantic network structure in a neurodynamical model of thinking, *Neural Networks*, **32** 147–158.

Osborn, A. F.: 1963, *Applied imagination: Principles and procedures of creative problem solving*, Charles Scribner's Sons, New York, NY.

Runco, M. A. and Pritzker, S. R. (eds.): 2011, *Encyclopedia of Creativity*, Elsevier, San Diego, CA.

Searle, J.: 1980, Minds, brains and programs, *Behavioral and Brain Sciences*, **3**(3), 417–457.

Sosa, R. and Gero, J. S.: 2012, Brainstorming in solitude and teams: A computational study of group influence, *International Conference on Computational Creativity*, 188–196.

Sosa, R. and Gero, J. S.: 2013, Multilevel computational creativity, *International Conference on Computational Creativity*.

Sosa, R. Gero, J. S. and Jennings, K.: 2009, Growing and destroying the worth of ideas, *Seventh ACM conference on Creativity and Cognition*, 295–304.

Stiny, G.: 2008, *Shape: talking about seeing and doing*, The MIT Press, Cambridge, MA.

Wiltschnig, S. and Onarheim, B.: 2010, Insights into insight. How do in-vitro studies of creative insight match the real-world complexity of in-vivo design processes, *Design Research Society International Conference*, Montreal.

Yamamoto, E., Goka, M., Fasiha, M. Y. N., Taura, T. and Nagai, Y.: 2009, Virtual modeling of concept generation process for understanding and enhancing the nature of design creativity, *ICED'09: International Conference on Engineering Design*, 101–112.

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EXPERIENTIAL INFLUENCES ON COMPUTATIONAL ASSOCIATION IN DESIGN

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Abstract. This paper presents a computational model of association in design that incorporates the ability to learn from experience. Experiments with an implementation of our model of computational design association, the interpretation-driven model, demonstrate this experiential influence. The challenges inherent in building computational models of association, and the potential offered by the interpretation-driven approach are discussed with reference to a typology of association learning.

Keywords. Computational design; association; experiential learning.

1. Introduction

Association, the process of connecting ideas, objects or situations in new ways, is critical to design thinking. Making new associations can allow the unfamiliar to be represented in terms of the familiar, providing new design ideas or aiding in the comprehension of a design problem. Associations can also enable ad-hoc categorisation or judgements of similarity, allowing disparate design elements to be compared in a context-sensitive way. Computationally modelling the process of association as it is used in design presents the challenge of capturing this flexibility, context-sensitivity and breadth of application.

Designers are inextricably influenced by their prior experiences. Each new design problem is perceived through the lens of all past design acts; a designer's memory is constructive (Gero, 1998). Computational models of cognitive

processes in design must reflect this experiential quality. For example, Suwa et al. (1999) discuss the "unexpected invention of design requirements", a process by which a designer observes something new in a representation of an emerging design, and that observation changes the course of the design process. That act of recognition is the designer drawing on their wealth of design experience, and its impact on the design process is one of many ways designers can "learn" from their past experiences. This research explores the ways in which learning from experience can be incorporated into computational models of association in design.

We have developed and implemented a model of computational association based on the principle of interpretation-driven search. The model and its capabilities have been previously documented in Grace et al. (2012). Our model is applied to the domain of perceptual associations between groups of shapes. In this model representations of each object to be associated are built, and then those representations are transformed until a new mapping can be made. These transformations are called "interpretations".

We present a set of experiments investigating how the persistence and recollection of these interpretations can enable a kind of learning in association. This kind of learning, "domain association experience", involves learning about how particular objects can be used to associate. Every association encapsulates a unique relationship between two objects, and it is challenging to generalise from this experience. Interpretation-driven association provides one method by which to approach this challenge.

2. Association and Experience

Studies of association-based processes (notably analogy and metaphor) in cognitive psychology have found that a subject's experience play a significant role in their associative abilities. Experiments suggest that significant training, examples or knowledge are required before a subject is likely to make deep, structural analogies rather than superficial surface-similarity comparisons (Forbus et al., 1994; Gick and Holyoak, 1980). This suggests the central role of well-structured domain knowledge as a precursor to association, and experiments in laboratory settings support the idea that analogical thinking is a domain of the expert. By contrast observational studies of analogy use in the real world (Dunbar, 2001) propose that familiarity with and immersion in a domain are sufficient, and that non-experts are still familiar with many potential analogical domains. Both of these hypotheses treat experience as a central component of association-based cognition, and psychological research in this area reflects this centrality.

By contrast computational models of associative reasoning are largely atemporal – they are not concerned with learning or with effects arising from the persistence of experiences. Association, analogy and metaphor are usually mod-

elled as independent processes that can be applied to arbitrary object representations. The nature of design as situated cognition (Gero, 1998) applied to a wicked problem (Rittel, 1988) makes it difficult to reconcile this approach with models of design thinking. Computational models of association can be and have been used as tools by designers, but the use of these tools is constrained by their inability to adapt to an evolving design context.

3. Kinds of Experiential Effects in Association and their Roles in Design

Broadly there are three different ways in which experience can influence an association process. This typology serves to contextualise the kinds of learning possible in models of association, to highlight what kinds of learning are challenging and why, and to provide a framework in which to place the learning capabilities of our interpretation-driven model of association.

3.1. DOMAIN OBJECT EXPERIENCE

This kind of experience is with the objects of the domain(s) being associated. It manifests as richer, more detailed representations of objects, and as representations of a greater variety of objects. It is not necessarily derived from associative reasoning – experiencing objects through other processes can provide useful knowledge about them. It is this first kind of association-influencing experience that most models of association are equipped to deal with: add more objects, or more information to the representation of existing objects, and the effect of this kind of experience can be approximated.

Dunbar's (2001) experiments contrast analogical reasoning capabilities in laboratory situations where subjects had just been taught facts about analogues with natural situations where subjects had been working with analogues regularly. It was found that capacity for deep, structural analogies is developed through sustained engagement with objects and ideas. This suggests that how objects are interacted with and how subjects build their knowledge of those objects through experience plays a significant role in association. This is consistent with the constructive nature of memory (Rosenfield, 1988) and certainly has parallels in design – a first-year architecture student does not become a master by reading about masterful works. Exploring how to model constructive learning about objects to be associated through experience is a topic for future research in association in design.

3.2. DOMAIN ASSOCIATION EXPERIENCE

This is experience using a particular object or objects in association processes. Knowledge is gained about how and when particularly objects can be mapped, and how to best represent objects for mapping. In language, for example, his can be seen

in concepts that are familiar and frequent sources for metaphor: war, evolution, flowering, gravity, etc. These ideas are used regularly in metaphorical comparisons and experience is gained about how they are typically represented. When next an association is constructed using one of these ideas, the experience of how to associate with them will have an impact. This differs from simply knowing more about the object (domain object experience) as the knowledge is association-specific.

This kind of knowledge is difficult to represent computationally. Every association consists of a unique mapping, and there is no guarantee that mappings involving objects that have previously been associated will bear any similarity to those previous mappings. Association is a generative process that constructs a new relationship where previously none existed. Each new association task can bring with it new objects to relate, and the relationship constructed between those two objects may bear no resemblance to any association the system has previously constructed. Drawing directly on a previous mapping may even be counterproductive – knowing that a kitten and a magazine can both lead to unexpected bleeding is of little use when trying to build a new association between a kitten and a cup of tea.

Incorporating domain association experience into computational models is of particular interest in design contexts. Design has been characterised as a cyclical interaction of reformulation and re-representation tasks (Schön, 1983) in which unexpected discoveries (Suwa et al., 1999) can transform the design space and lead to creative designs (Gero, 1990). A designer's understanding of a design problem undergoes continual transformation, with many relationships being drawn to previous states, other designs and related ideas. Each of these relationships requires association, and these association tasks are tightly coupled with the designer's evolving understanding.

3.3. GENERAL ASSOCIATION EXPERIENCE

The final, and most abstract, kind of affect of experience on association is general association experience. This is knowledge about association itself – how and where to apply associative reasoning and how to approach association problems. Ball et al. (2004) find that not only do expert designers use significantly more analogical reasoning during design than novices, but that the analogies they use are more likely to be schematic – that is, based on familiar types or categories of problems rather than specific, concrete examples of prior experience. This suggests that experienced designers learn both how to apply association in different and more structured ways, in addition to just learning how to apply association more often; experienced designers possess more general association experience. This kind of abstract skill acquisition is beyond the scope of most current attempts to computationally model association.

4. Experience in the Interpretation-driven Model of Association

We have developed a model of computational association in design that is founded on the principle of interpretation-driven search. The model has been previously described in Grace et al. (2011) with a discussion of an implementation of the model and the results it produced in Grace et al. (2012). This research explores the ability of the interpretation-driven model of association to learn from its experiences.

Interpretation-driven search is a framework for association in which the search for mappings occurs in a parallel, iterative interaction with an interpretation process. This interpretation process transforms the representations of the objects being associated, permitting new possible mappings that could not have existed between the untransformed representations. We have implemented the model in the domain of ornamental design, developing a computational system that can make visual associations between vector images based on shapes within those images and the relationships between those shapes. We have demonstrated that this implementation can produce a variety of interesting associations and that it is a viable framework for future association research.

The interpretation-driven model of association provides a potential new approach for domain association experience. The model constructs and stores interpretations that can be used to transform objects in ways that enable mappings between them. These interpretations are defined in a general way that allows them to be applied to any object, not just the objects involved in the association during which they were constructed. Interpretations are a "way of seeing" – to adopt a new interpretation is to adopt a different perspective. These interpretations can be stored and re-used in later association problems, allowing that different perspective to be adopted again.

The recollection of previously experienced interpretations is more generally applicable than the recollection of mappings. For example, the specific mapping in the example given earlier associating kittens and magazines is that the kittens claws can produce painful scratches while the paper's thin edges can produce painful cuts. This association can be produced by interpreting the two objects in the context of the concept "unexpected danger". That interpretation could then be re-used in another situation, such as associating online communication and painkillers, for which the specific mapping between claws and edges would be useless. Our computational association system is capable of this kind of interpretation re-use in the visual domain.

4.1. EXPERIMENTAL SETUP

An experiment has been conducted to investigate the ability of the interpretation-driven model of association to learn from domain association experience. The degree to which an association problem with multiple possible outcomes can be influenced by priming the system with other association problems will be

assessed. It will be shown that, through recollection of interpretations, the system is capable of being influenced by previous association experiences even when those experiences involved different objects. The ability to prime the implementation of the model and bias it towards particular results will demonstrate that the model exhibits the potential for learning about how to associate within a domain.

The experiment is conducted using the five objects shown in Figure 1. The black-outlined shapes form the images themselves, the light grey borders indicate the boundaries of each image object, and the labels identify features extracted from the images by the system. There are three types of relationship between features in the objects in this experiment: "relative orientation", "vertical distance" and "shared vertex". Objects 1, 2 and 3 are used in associations to prime the system, and an association between Objects 4 and 5 with multiple possible outcomes is then affected by that priming.

Three trials were performed using these objects, each culminating in an association between Objects 4 and 5. The first trial serves as a priming-free control while the second and third trials involve a priming association. The trial setups are shown in Table 1, which describes the objects and association problems used in

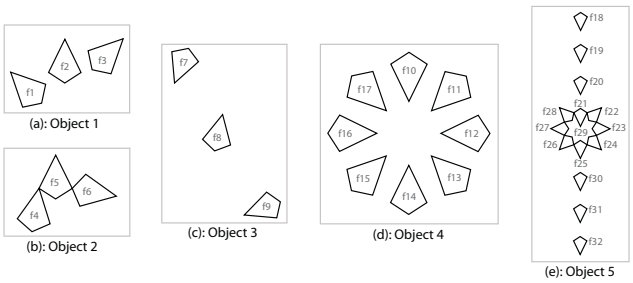

Figure 1. The objects used in the priming experiment. An association between either Objects 1 and 2 or between Objects 1 and 3 is used to prime the interpretation system. An association between Objects 4 and 5 is then constructed.

Table 1. The priming association and the dependent association of each of the three trials. The result of each trial is the distribution of interpretations used in constructing associations.

	Priming association	**Dependent association**
Trial 1	*None*	Object 4 and Object 5
Trial 2	Object 1 and Object 2	Object 4 and Object 5
Trial 3	Object 1 and Object 3	Object 4 and Object 5

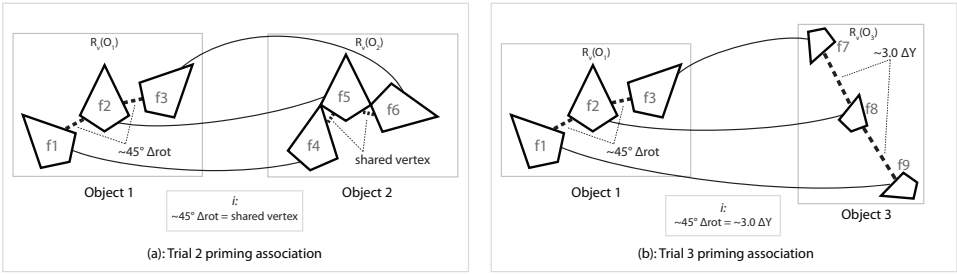

Figure 2. The association produced in the priming steps of Trials 2 and 3. The interpretations used in these associations influence the dependent association.

each step of each trial. Each trial is repeated 100 times, re-initialising the system between trials to erase the effects of priming. A distribution of the interpretations used in the association solutions is produced.

Each of the priming associations has been constructed to produce the same interpretation every time it is run. These predictable associations can be seen in Figure 2. The notation is the same as in Figure 1 with the addition of solid lines joining the two objects indicating what features have been mapped, and thick dashed lines joining features within each object indicating the relationships on which those mappings are based. The priming association used in Trial 2 (shown in Figure 2a) uses an interpretation in which the relationship "~45° difference in rotation" is treated as being the same as the relationship "share a vertex", and therefore that interpretation is known to the system when it performs the dependent association in that trial. The priming association used in Trial 3 (shown in Figure 2b) uses an interpretation in which the relationship "~45° difference in rotation" is instead treated as being the same as the relationship "3.0 units above", which instead makes that interpretation known to the system.

4.2. EXPERIMENTAL RESULTS

After priming in Trials 2 and 3, or the lack thereof in Trial 1, the system constructs an association between Objects 4 and 5. The interpretations used to produce that association in each trial are shown in Figure 3, which shows the percentage of associations that use each of the two primed interpretations. The percentage of associations that used all other possible interpretations is also shown.

Figure 3 shows that priming significantly increases the likelihood of an interpretation being used in association. The primed representations (the dark grey one in Trial 2 and the medium grey in Trial 3) were all capable of being independently

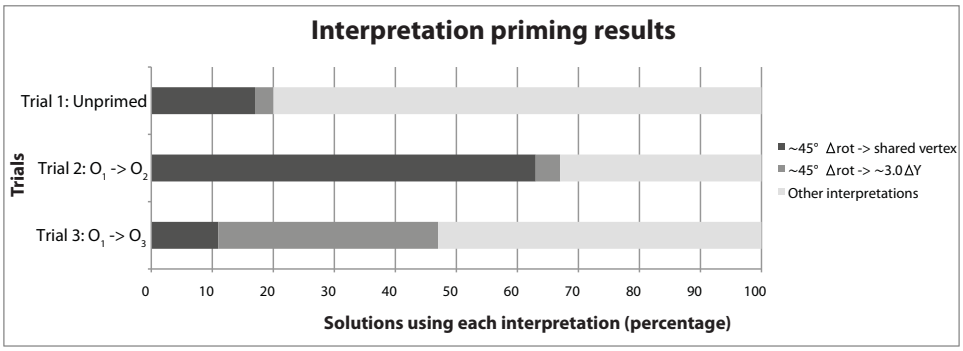

Figure 3. The distribution of results in each trial, showing the percentage of associations that used each of the primed associations.

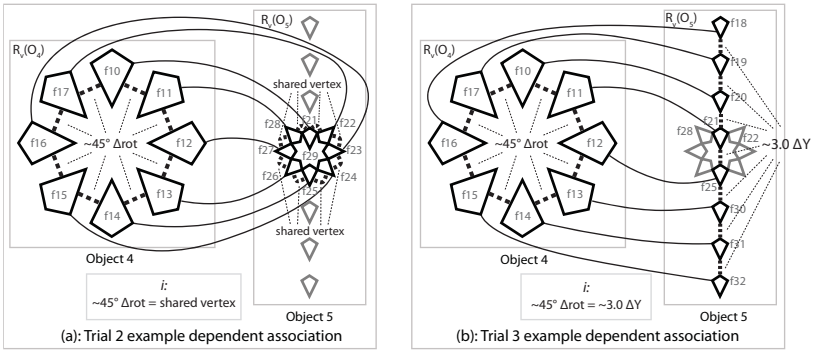

Figure 4. Associations between Objects 4 and 5 produced in Trial 2 (a) and Trial 3 (b).

constructed by the system and thus both appeared in all three trials. However, the experience of using the primed interpretation in a past association significantly increased the percentage of runs in which that interpretation was used in both primed trials.

The interpretation equating 45° of orientation difference with sharing a vertex was used in 17% of associations without priming in Trial 1, but this increased to 63% of associations performed after having previously used that interpretation successfully in Trial 2. Likewise the interpretation equating the orientation difference with vertical spacing increased from 3% of all associations to 36% after priming in Trial 3. Examples of each of these primed associations between Objects 4 and 5 can be seen in Figure 4.

The difference between absolute likelihood of these two solutions is explained by differences in the underlying graph structures, which serves to demonstrate that experience can affect the adoption of interpretations common and rare alike. The other interpretations used to construct this association which are not relevant to the priming in this experiment included equating 90° or 135° with various distances and the shared vertex relationships.

These results show that the association system is able to learn from experiences by applying interpretations that it has used before. This demonstrates the interpretation-driven model of association's capacity for domain association learning.

5. Discussion

This proof-of-concept experiment with simple visual objects demonstrates that associations produced in the past by the interpretation-driven model of association can directly affect the associations it will produce in the future, even when those associations involve different objects. In our typology of kinds of experiential influence in association this constitutes domain association learning, a useful behaviour for application in design.

Applying knowledge gained from constructing an association between two objects to the construction of a new association between two different objects is a challenging problem. Interpretation-driven association makes this possible through the explicit representation of the transformations applied to object representations. Interpretations can be constructed, evaluated and stored for later use in this approach to computational association. These interpretations are transferable to different problems in a way that the specific mappings possible by applying those interpretations are not. This approach is applicable to domains other than the simple vector images used in our experiments as the behaviours are properties of the model not the computational implementation of that model we have developed.

The tendency of the re-use of past experience to lead to over-convergence upon known solutions is mitigated in the interpretation-driven model by the discounting of commonly found interpretations. Known interpretations are far more likely to be found first, but all interpretations remain discoverable.

The interpretation-driven model of association incorporates processes that enable the remembering of previously successful interpretations. In the current implementation these processes are only partially implemented, permitting literal recall of past experiences without re-constructing them to fit the current situation. The current system can only reapply interpretations exactly as they were previously used, and does not possess the capacity to abstract, generalise or contextualise the experiences it has learnt. The experiments performed in this paper have demonstrated that even this simple, literal recall of past experiences can influence behaviour.

Previous interpretations that can be applied to a problem could all theoretically have been constructed by the interpretation generation system and used in association without previous experience. Demonstration of this can be seen in Trial 1 of the experiment, where both "priming" solutions were still found even though they were not primed for. This means that any interpretations applied through experience could always have been found without experience – given enough time. This limits the possibility for creativity according to some definitions (Boden 1990, Gero 1990). However, interpretation recall can lead to solutions that would have been extremely unlikely.

This research has demonstrated that it is possible to learn from experience in computational association and reapply that experience to different problems. This is significant for research in computational association in design as design presents an environment with rapidly evolving representations in which the ability to reconstruct and reapply past knowledge is critical. Schön (1983) describes design as a "reflective conversation, a product of repeatedly associating the current design with past experiences, and this research is a step towards computationally representing that discourse".

References

Ball, L., Ormerod, T. and Morley, N.: 2004, Spontaneous analogising in engineering design: a comparative analysis of experts and novices, *Design Studies,* **25**(5), 495–508.

Boden, M.: 1990, *The Creative Mind,* Abacus.

Dunbar, K.: 2001, The analogical paradox: why analogy is so easy in naturalistic settings, yet so difficult in the psychology laboratory, *Analogy: Perspectives from Cognitive Science,* MIT Press.

Forbus, K., Fergusun, W. and Gentner, D.: 1994, Incremental structure-mapping, *Proceedings of the Sixteenth Annual Conference of the Cognitive Science Society,* 283–288.

Grace, K. S., Gero, J. S. and Saunders, R.: 2012, Applying interpretation-driven association to design domains, *Circuit Bending, Breaking and Mending: CAADRIA2011*, Hong Kong, 453–462.

Grace, K. S., Gero J. S. and Saunders, R.: 2012, Constructing computational associations between ornamental designs, *Beyond Codes and Pixels: CAADRIA2012*, Hong Kong, 37–46.

Gero, J. S.: 1990, Design prototypes: a knowledge representation schema for design, *AI Magazine*, **11**(4), 26–36.

Gero, J. S.: 1998, Conceptual designing as a sequence of situated acts, *in* I. Smith (ed.), *Artificial Intelligence in Structural Engineering,* Springer, 165–177.

Gick, M. and Holyoak, K.: 1980, Analogical problem solving, *Cognitive Psychology*, **12**, 306–355.

Rittel, H.: 1988, The reasoning of designers, *Working paper*, Institut für Grundlagen der Planung.

Schön, D.: 1983, *The Reflective Practitioner*, Basic Books.

Suwa, M., Gero, J. S. and Purcell, T.: 1999, How an architect created design requirements, *Design Thinking Research Symposion: Design Representation*, vol. 2, MIT Press, 101–124.

Rosenfield, I.: 1988, *The Invention of Memory: A New View of the Brain*, Basic Books.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 873–882. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

TESSELLATING FREEFORM SURFACES WITH BOUNDARY-DRIVEN ANALYSIS

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Abstract. In this paper, we look at the surface tessellation problem, in particular, the problem of meshing a surface with the added consideration of incorporating constructible building components. When a surface is tessellated into discrete counterparts, certain conditions usually occur on the surface boundaries that are caused by trimming operations; for example, irregularly shaped panels at the trimmed edges. We present an algorithmic approach to tessellating quad-dominant mesh surfaces to deal with such irregular boundary conditions, and demonstrate its application through surface subdivision examples.

Keywords. Freeform surfaces; boundary-driven analysis; surface tessellation.

1. Introduction

In contemporary architectural and design practice, there is an increasing interest in complex freeform shapes, pioneered by such avant-garde designers as Frank Gehry and Zaha Hadid. A NURBS (Non-Uniform Rational Basis Spline) surface is a commonly exploited mathematical model for early freeform shape construction. To manifest a NURBS surface, a discrete mesh model is employed. The meshing process generates an approximation of the given freeform geometry.

In order to design, model, and, subsequently, fabricate intriguing, sometimes intricate, freeform shapes, this research looks at the surface tessellation problem, which is an extension of the meshing process with an added consideration of incorporating constructible building components. There is a close relationship and analogy between the elements of a mesh and components of a freeform design, for example, face to panel, edge to structural frame, and so on.

1.1. TESSELLATING SURFACES WITH IRREGULAR BOUNDARY CONDITIONS

The features of a given surface boundaries are essential for surface tessellation. For example, the boundaries (also called edges) delineate the appearance of a freeform shape and indicate where surface analysis starts and where it ends. These boundaries also identify whether the surface has been trimmed in the interior or exteriorly. When tessellating a surface into its discrete counterparts, there are certain conditions that usually occur at the surface boundaries, which are created by the trimming operations, for example, irregularly shaped panels at the trimmed edges. This is a commonly seen problem in freeform architecture designs, where, for instance, an entrance opening has been introduced. By looking at surface boundary conditions for given tessellation patterns, this paper presents an algorithmic approach to boundary-driven mesh generation. Specifically, the quadrilateral mesh is used to exemplify this approach to the formation of pattern-based freeform structures with irregular boundary conditions.

The objective of this research is to present a general algorithmic solution to discretizing freeform surfaces with pattern-based elements, and to develop strategies for solving constraints from irregular surface boundaries.

1.2. RESEARCH BACKGROUND

Applying computational geometry principles for freeform manifestation places an emphasis on meshing arbitrary surfaces into fabric-able building components. Owing to the relative ease of constructing with planar components, it is preferable to approximate freeform surfaces by planar face elements, such as triangles. However, it is almost always nearly impossible to create a well-structured mesh for any arbitrary surface using simply regular elements (Pottman et al., 2008). One possible solution is to begin with a well-structured mesh, and then consecutively subdivides and optimizes the mesh towards the target surface. This process relies heavily on the preparation of an initial coarse mesh and on how well this initial mesh represents the target shape (Pottmann et al., 2007). In most freeform architectural design, it is difficult to reverse-engineer any arbitrary surface into a representative course mesh. An alternative approach presented by Cutler and Whiting (2007) looks at a re-meshing technique by iteratively clustering neighbouring mesh elements and fitting them onto the closest planes. Their result demonstrates an algorithmic approach to post-restructuring an originally triangulated mesh into planar elements for architectural fabrication.

Additionally, the bubble mesh (Shimada and Gossard, 1995) presents a physics-based algorithm to automate mesh generation by simulating bubble packing. The strengths of this algorithm are in its ability to control size, anisotropy and

orientation of mesh formation. This paper shares the same interest in automating the meshing process as the bubble mesh. Yet, this research focuses more on minimizing the irregular regions that are created from the given boundary conditions. The contention is that by examining the boundary conditions of a target surface, a well-structured mesh can be generated and thus provides a coherent tessellation pattern for further freeform penalisation design.

2. Boundary-Driven Mesh for Surface Penalisation

Penalisation is the process of realizing a freeform surface by a collection of constructible components, in particular, face-based panels and supporting structures. From a parametric modelling perspective, each panel can be procedurally built on a given polygonal shape, namely, the pattern of the local boundary representation. Underlying a quadrilateral panel are four vertices that define the local boundary, a quadrilateral face. Contemporary approaches to modelling such panels are primarily based on surface isoparameters, u and v. Isoparameterization is a process of mapping two-dimensional parameters u and v to a three-dimensional manifold.

While these approaches are simple and efficient, they are, at the same time, limited. For instance, isoparameters do not distinguish between the curvatures of adjacent surface patches, which might affect both aesthetic appearance and final manifestation. Nor do the parameters control the size of the sub-surface generation. Commonly, a uniform parametric interval is employed; this usually results in non-uniform sub-surface generation. The size of each panel is in fact closely related to the initial control polygons. The control polygons govern the control points, which are used to interpolate the ultimate surface presentation. If the vertices of the control polygons are uniformly distributed, an equi-dimensional patch is more likely to be generated. However, given the freedom with which control points can be modified in the modelling environment, they rarely remain uniformly distributed once designers start manipulating arbitrarily.

Unlike curve decomposition wherein a curve could be divided into equidistant segments by a prescribed circle, there is no general way of dividing a surface into uniform sub-surfaces. Current tessellating applications for architectural design rely mainly on uniform isoparametric control. That is, patches are generated according to the isoparametric domains. To construct equi-dimensional sub-surface regions, one possible solution is by iteratively optimizing cell sizes until they reach a specified threshold. However, with the growing complexity of irregular boundary conditions, the task of converting an arbitrarily trimmed surface into well-structured sub-surface regions is challenging. For instance, Figure 1 shows the west façade of Zaha Hadid's Next-Gene Museum in Taiwan (Hadid, 2008).

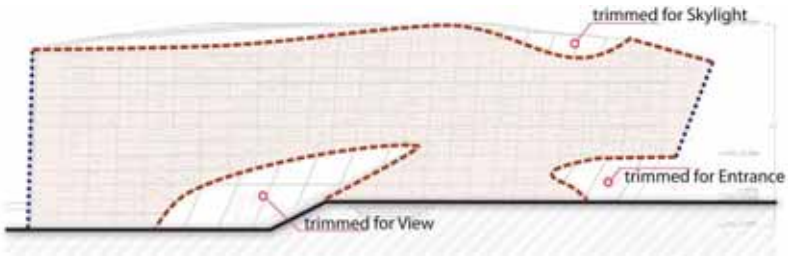

Figure 1. Illustrated west elevation for trimmed boundaries (Image modified from the Next-Gene Museum by Zaha Hadid, 2008).

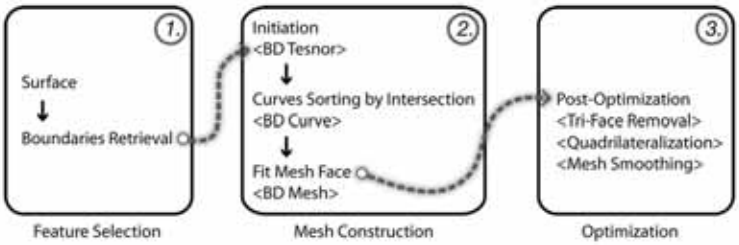

Figure 2. The proposed workflow for boundary-driven mesh optimisation.

The figure illustrates boundary conditions formed by trimming for various purposes, such as trimming for entrance, view, and skylight. The hypothesis is that by taking boundary conditions into considerations, irregular panels at these trimming edges can be removed and a coherent underlying tessellation scheme can be achieved.

In order to solve the problem of tessellating surfaces with irregular boundary conditions, we propose a workflow based on a goal seeking process with the following three major stages (see Figure 2). The workflow depends on the formation of a BDTensor, BDCurve, and BDMesh.

2.1. BOUNDARY-DRIVEN TENSOR AND CURVES

A boundary-driven tensor (BDTensor) pertains to information on a location of interest, and its corresponding weighted vectors. The output of a tensor node yields directional projections, which are used for navigating the given surface domain. The Inverse Distance Weighting (IDW) method (Shepard, 1968) is

adopted in the BDTensor interpolation by taking a given number of sampling values from the feature boundaries. The equation is written as follows:

$$T(u) = \sum_{i=0}^{N} \frac{w_i(u)\, u_i}{\sum_{i=0}^{N} w_i(u)}, \quad w_i(u) = \frac{1}{d(u,u_i)^{\rho}}, \quad 0 \le i \le N \tag{1}$$

N is the number of nodes utilized for interpolation and could be potentially less than number of boundary edges. u denotes the target node. Each w_i is a weighting function. Each u_i is a local interpolating node on a feature boundary edge and d represents the distance function from a boundary node u_i to the target node u. ρ is the power parameter to smooth out the influence of the sampling boundary nodes.

Figure 3 illustrates a BDTensor P, which is interpolated by locally influential nodes, pA, pB, pC, and pD, on the feature boundaries, respectively E_A, E_B, E_C and E_D. After iteratively moving the node toward its next location along the interpolated direction, a BDCurve is constructed. The iso-parametric curves are shown shaded green using a dashed pattern. BDCurves are shown coloured blue or red with arrows.

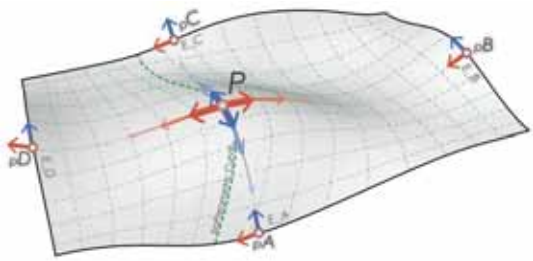

Figure 3. Conjugate curves derived from boundary-driven computation and the underlying isoparametric grid.

2.2. BOUNDARY-DRIVEN CURVE INTERSECTION

When boundary-driven curves (BDCurves) are created, they are grouped by their origin, namely the directions along which they were derived. Then, curve-to-curve intersections are evaluated to formalize the interconnected network. In this connected structure, the graph nodes (intersection points) represent mesh vertices. The sorted nodes are then revisited to build the corresponding mesh edges and faces, as described in section 3.1.

The generated mesh nodes in the network are not necessarily the same as the BDTensors created in the first step. Instead, they are remapped nodes on the curve network, which governs the formation of the boundary-driven mesh.

3. Meshing with the Boundary-Driven Curve Network

To optimize a target surface with discrete elements, we start from a representative curve network derived from the feature boundary conditions. A mesh topology solver is then employed to construct the corresponding mesh faces and edges from this interconnected curve network. The algorithm initiates a search by visiting existing mesh nodes in the network and consecutively determines the shortest path between its current neighbouring nodes to form corresponding faces. The pseudo-code below describes the process:

```
foreach mesh node in the network:
   foreach pair of current neighboring nodes [nStart, nEnd]:
      if (existing face does not contain [node, nStart, nEnd])
      {
          find the shortest path P: starting from node, via nStart, to nEnd
          create new mesh face from the path P, and update it to the mesh
          topology
       }
```

3.1. MESH TOPOLOGY SOLVER

To create a mesh using the sorted curve network, a topology solver is employed to construct mesh face from only local neighbour relationships. Figure 4 illustrates the topology solver. When mesh nodes are sorted, their topological relations are also structured in a counterclockwise fashion. The shortest path approach is adopted to fit a best-matched mesh face. This searching process terminates immediately when a shortest path is found, for instance path of V_4-V_7-V_8-V_5, or, when a

Figure 4. Fitting mesh faces by shortest path search.

face element that shares the same nodes in the initial search set already exists. By sweeping through all mesh nodes in the network, the initial mesh is constructed.

3.2. MESH REFINEMENT

The objective of mesh refinement is to remove skewed triangles, and to construct quad faces from arbitrary polygonal faces. Conditions and procedures for refining the mesh elements to create a quad mesh are discussed below.

3.2.1. Skewed Triangle Removal

To control whether a triangle face is skewed for removal is specified by a threshold parameter, which is calculated by the ratio of the smallest and largest interior angles of a triangle face. Figure 5 illustrates skewed triangle removal carried out by vertex replacement. The vertex with the largest interior angle of the triangle is removed, and is replaced by its nearest vertex in the triangle.

Figure 5. Skewed triangle removal.

3.2.2. Quad-dominant Mesh

The polygonal faces are subdivided to convert the initial mesh into a quad-dominant mesh containing only quadrilateral faces in the network. The subdivision process is carried out by edge mid-point and face centre vertex insertions, as shown in Figure 6.

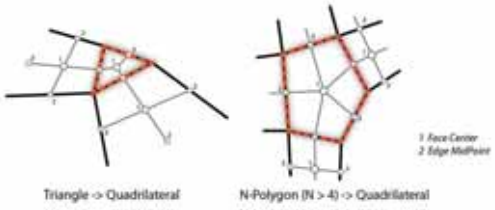

Figure 6. Quad meshing by face center and edge midpoint insertion.

3.2.3. Mesh Smoothing

The quality of the resulting quad-mesh can be improved by mesh smoothing, also called mesh relaxation. We consider a Laplacian smoothing algorithm (Herrmann, 1976) with local perturbation to ensure that the smoothed result conforms to the original input surface. To start, we compute the new vertex locations by a finite difference approximation of the Laplace operator, which moves a mesh vertex toward the centroid of the connected vertices. The equation is written as follows:

$$P_{new} = \frac{1}{n}\sum_{i=0}^{n} \alpha_i P_i.$$

where αi is the weighting factor for each connected mesh vertex.

As the initial *BDCurve* network is generated from the conjugate relationship, the connected vertices of a *BDMesh* vertex will likely form a convex polyhedron. (Exceptions occur at vertices on the surface boundaries). For interior vertices bounded by convex hulls, the new locations derived from centroids of these polygons remain inside the original boundary. This property ensures homogeneous mesh generation and maintains the original anisotropic configuration. However, for peripheral vertices on the original boundaries, special treatment is needed. For example, vertices that are moved away (inside or outside) the original boundaries will need to be adjusted so that the mesh stays as close as possible to the original surface. Two cases of mesh vertex replacements are illustrated in Figure 7. Corner vertices belong to the third scenario where they will not be modified in order to keep the original boundaries intact.

Local modulation of mesh vertex location is through vertex perturbation. There are two types: vertex-to-edge and vertex-to-face perturbations. Vertex-to-edge

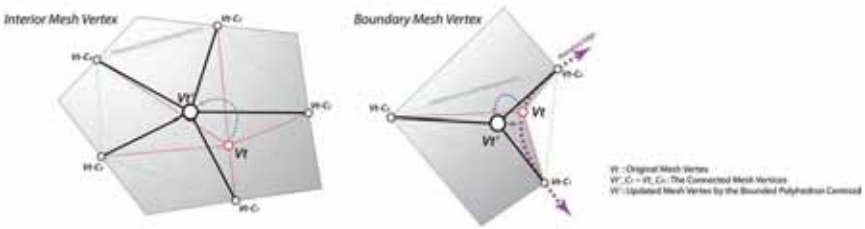

Figure 7. Mesh vertex replacement
(Left) Interior mesh vertex: Replaced by the centroid of a convex polyhedron;
(Right) Boundary mesh vertex: Moved from the original boundary and then adjusted by vertex perturbation.

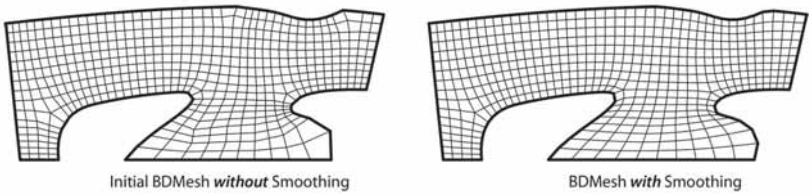

Figure 8. Mesh smoothing
(Left) BDmesh without smoothing; (Right) Smooth BDmesh by vertex perturbation.

perturbation moves the mesh vertex back to the closest boundary and, likewise, vertex-to-face perturbs the vertex onto the input surface. By so perturbing the mesh vertices either to the nearest location on the boundaries or onto the surface, the refined *BDMesh* can better represent the given surface. It also conforms to the given boundary conditions. Figure 8 shows the result of the *BDMesh* after smoothing by vertex perturbation. The resulting mesh not only has more equi-dimensional mesh faces but also relaxed boundary edges.

3.3. SEMI-REGULAR TILING APPLICATIONS

Owing to the topological complex nature of the irregular boundary conditions, it is almost impossible to optimize any arbitrary surface by just regular regions. Notwithstanding, the algorithm presented in this paper optimizes the result by minimizing the number of irregular regions. The proposed approach not only generates a mesh, which conforms to the boundaries it inherits, but, at the same time, it minimizes the irregular regions that might be generated during the meshing process. From a given quad-dominant mesh, other pattern generation can be achieved. Figure 9 illustrates combining an underlying quad pattern with an offset

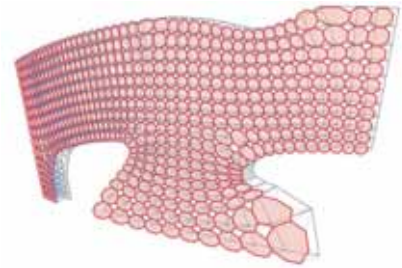

Figure 9. Combining a regular quad pattern with a truncated square pattern for customized surface tessellation.

truncated square pattern. The integrated pattern forms fundamental elements for surface tessellation. These can be further developed to other constructible elements, such as mesh edges for structure trusses, mesh faces for surface panels.

4. Discussions and Conclusions

Customizing and controlling the tessellation scheme for any arbitrary surface is of some interest to both the computational geometry and architecture communities. Conventionally, tessellating a surface is often limited to iso-parameterization. In this paper, we investigate an algorithmic approach not only for automating the mesh generation from a given surface with irregular boundary conditions but also, at the same time, demonstrate the usage of well-structured meshes for pattern exploration.

There are still rich areas for further research. For instance, improved control, from single to multiple boundaries, needs to be investigated. Potentially such control can be specified as user input. By doing so, the approach presented here becomes more amenable to real design exploration. Additionally, other surface examples can be explored to ensure robustness of the approach and we consider using more Archimedean patterns as examples to demonstrate the potential applications for customizable surface tessellation.

Acknowledgements

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References

Akleman, E., Srinivasan, V. and Mandal, E.: 2005, Remeshing schemes for semi-regular tilings, *The International Conference on Shape Modeling and Applications*, 44–50.

Cutler, B. and Whiting, E.: 2007, Constrained Planar Remeshing for Architecture, *Graphics Interface* 2007, Montreal, Canada, 11–18.

Hadid, Z.: 2008, *Schematic Design Report for Next-Gene Architecture Museum*, Graduate Institute of Architecture, National Chiao-Tung University, Hsinchu, Taiwan.

Hermann, L. R.: 1976, Laplacian-isoparametric grid generation scheme, *Journal of Engineering Mechanics*, **102**(EM5), 749–756.

Pottmann, H., Asperl, A., Hofer, M. and Kilian, A. (eds.): 2007, *Architectural Geometry*, Bentley Institute Press, Exton, PA.

Pottmann, H.: 2008, Geometry of Architectural Freeform Structures, *Proceedings of the 2008 ACM symposium on Solid and Physical Modeling*, ACM New York, 9–9.

Shepard, D.: 1968, A two-dimensional interpolation function for irregularly-spaced data, *Proceedings of the 1968 ACM National Conference*, 517–524.

Shimada, K. and Gossard, D. C.: 1995, Bubble Mesh: Automated Triangular Meshing of Non-Manifold Geometry by Sphere Packing, *ACM Third Symposium on Solid Modeling and Applications*, 409–419.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 883–892. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

TEMPERA

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Abstract. This paper explores the characteristics of painting developed during the Nineteenth century, and specifically updates the use of matter and brushing techniques invented by a group of painters called "Impressionists". In that period, impressionist artists began to brush "tempera" on a canvas as a malleable matter able to emphasize an accurate depiction of light in its changing qualities. Thick brush strokes left on the painted surface revealed the master' gesture and completely changed the way to represent reality. Stimulated by the recent advancements in digital technologies, this paper looks for methodologies able to transfer impressionistic painterly innovation into a contemporary digital 3D environment and investigates how paint behaves when morphing from a photorealistic depiction of Nature to a disfigured one. In particular, reality-based 3D information, first frozen by a laser scanner into a digital geometry, slowly melts into liquid paint on a colour palette. While colours mix, the geometrical matter that constitutes the photorealistic scanned reality and its details disappear into primitive paint clog that are mixed and brushed into new colours and shapes able to create novel atmospheric and chromatic effects.

Keywords. Tempera; laser scanner; 3D painting effects; design creativity.

1. Introduction

Through centuries the achievements in scientific research have often been accompanied by cultural renovations that generally required different means of communication of new visions and ideas. In some cases, these achievements were transferred from one field to another, such as, for example, from Physics to Arts,

that therefore became a fervent context to experiment new means of representation and expression.

During the Renaissance, for example, scientific research developed new methodologies and tools that allowed a deeper and wider observation of reality. In that period, Nature offered a wide variety of case studies in which investigations were conducted using these new technologies. Botany, Anatomy and Astronomy became the first privileged fields in which scientific research experimented and developed new codes and techniques of graphic representation. The rigor of scientific illustrations was generally obtained by the extreme faithfulness of each single detail that conferred objectivity to the entire image.

But if on one hand the circulation of these drawings contributed to spread knowledge, it is true that the beauty and fascination of these realistic representations soon was able to display scientific illustrations under a different light and provided a new iconic repertoire that inspired and influenced different artistic fields. In some cases, for example, these drawings quickly became independent from the treatises in which they were collected and indeed became paintings. In particular, the collection of objects derived from Nature and their compositions expressly created in the studios of painters willing to perfect their technique of faithfully reproducing reality, charged these representations of expressivity and symbolic meanings and gave rise to the birth of Still Life. This last was conceived as a specific genre of painting that manifested itself in different variations, ranging from "florilegi", where natural elements were isolated from their contexts, to the representation of landscapes, where they were included inside wide settings.

Four centuries later, Nature was chosen as a privileged subject of impressionist paintings in which a completely different language was investigated. Within this movement, representation techniques and matter became the instruments through which investigations where conducted with the aim of exploring new possibilities of communication where human perception and experience were crucial elements.

If compared with the techniques adopted by Renaissance painters that aimed at objectively reproducing reality, the realism of impressionist paintings was not guaranteed by the faithful representation of each single detail of a scene, but it was instead the result of the transposition of a sensorial experience on canvas.

2. The Tempera Project

2.1. PROJECT AIMS

These remarks gave impulse to the present a research that continues a former project called "Synthetic" (Manferdini and Manferdini, 2011). Starting from the

digital 3D acquisition of natural elements, that project explored the potential of digital technologies in the survey of micro-scale details, as well as in the magnification, manipulation, management and fabrication of the developed information. Within that research, natural materials were considered the sources that inspired new hyper-realistic sensory effects to be reproduced on surfaces in architectural contexts.

The resulting methodology developed by that workflow led to the present research, in which representation methodologies and techniques derived from painting are transposed to 3D digital environments using digital technologies in order to create novel atmospheric and chromatic effects to be used in architectural envelopes.

2.2. MOTIVATION

The interest in this research is to update the contribution to communication offered by painters in the 19th century, transferring their technical innovation into a contemporary set of digital tools. In that period, Art and Science were strictly connected. For instance, the corpuscle theory of light developed by Newton in the 18th century was the background on which the impressionist movement grew (Newton, 1704). One century later, scientific observations of physical phenomena gave impulse to different theories about matter and energy (Buchner, 1864; Janet, 1866; Le Bon, 1905) that gave substance to the new conception of matter that gradually evolved from its traditionally static characteristic into a more fluid and intangible one (Adhemar and Clark, 1974). Within the impressionist movement, painters began to measure themselves with their ability to observe the changing physical properties of matter and light and started dealing with the problem of the reproduction of colour and radiometric characteristics of matter.

In addition to these aspects, in that context the relationship between pictorial art and scientific research was also influenced by other aspects. In that period, for example, a new range of pigments were produced by the chemical industry that gave new consistency and brilliance to paints. Furthermore, the possibility to use portable tubes of oil paintings contributed to the spread of the “en plein air” painting and to the extensive use of “alla prima” techniques. As a consequence, the rapidity and thickness of brush strokes gave plasticity and sculptural characteristics to paintings; colours were therefore not considered just for their pigment characteristics, but they became the result of changing lighting effects on canvas. Taking advantage of the achievements in the optical research, impressionist painters analyzed illumination processes and reproduced natural lighting effects by splitting the micro phenomena that they observed and by creating an overall vibrating impression of colour, natural light and weather conditions. This final

result was generally achieved by adding and overlaying single brush strokes whose tint was determined by the direct observation of the amount and quality of rays of light that each substance absorbs and reflects.

This renovated language progressively abandoned the faithful imitation of reality determined by the accurate reproduction of every single detail of a composition and moved towards a more eidetic representation where subjective perception and experience became protagonist of the canvas.

Within the communication process, the observation of those paintings represents the moment in which each single colour and radiometric effect is merged and the overall luminous unity and harmony of the iridescent colour that the painter scattered is re-established (Moffett, 1986).

Similarly to the cultural renewal that represented the background for the impressionist movement in the painting field, the digital revolution recently transposed the results of scientific research in the computer graphics field.

Taking advantage of these developments, the present project searches for methodologies to transfer impressionistic painterly innovation into a contemporary digital 3D environment (Meier, 1996; Daniels et al., 2001; Baran et al., 2011) and investigates how paint behaves when morphing from a photorealistic depiction of Nature to a disfigured one. In particular, the "Tempera" project takes on a classical exercise of Still Nature as a testing ground for the different representations of matter.

2.3. METHODOLOGY

As in the last two decades 3D laser scanning has completely changed the way we can access reality and has allowed us to manage 3D information and to run simulations within digital environments (Bernardini and Rushmeier, 2002; Blais, 2004; Lohr et al., 2010; Wang, 2011; Guidi and Remondino, 2012), the present project was organized following a workflow in which the acquisition of real data constitutes the first step.

The present case studies were chosen among a wide variety of natural elements derived from the plant kingdom. Such elements were selected because of their particular geometric characteristics. As far as spatial characteristics are concerned, geometric complexity is represented by the intricacy of small scale details or by the composition of single elements in clusters, while as far as their radiometric properties are concerned, the brightness of colours was one of the main peculiarities upon which the present case studies were selected.

The small dimension of details and the need to restore high definition 3D models aimed at being magnified for further manipulations led to the use of triangulation laser scanners. As a matter of fact, within the present project, this technology represents the best compromise in terms of portability, accuracy, detail

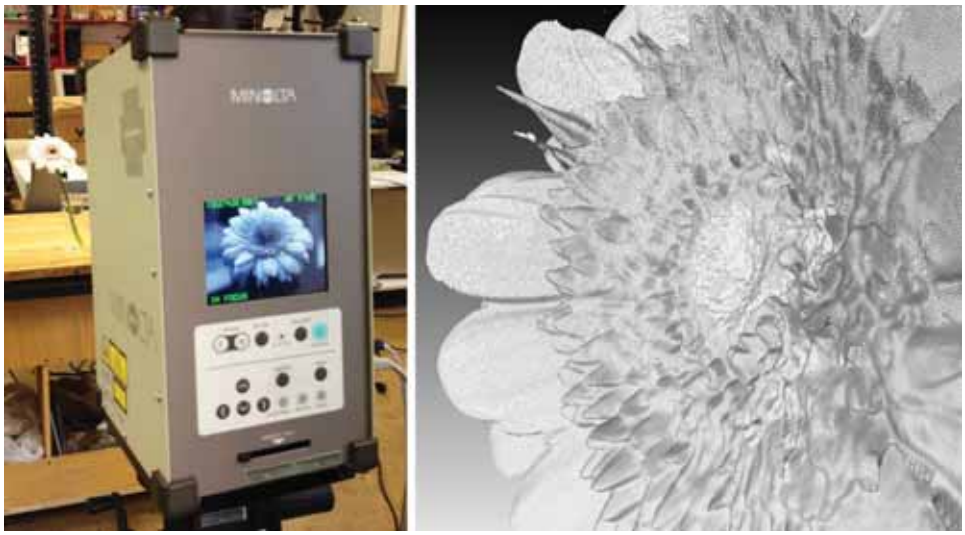

Figure 1. Left, 3D laser scanning of a flower. Right, details of the acquired geometry.

and management of data. In particular, both NextEngine and Minolta Vivid 900 were used within the present project (Figure 1).

Afterwards, the surveyed information was translated into 3D realistic geometry (Figure 2) and manipulated adding painting effects to reality-based 3D models (Figure 3). During this step, meshes slowly melt into liquid paint on a colour palette using the Pixologic ZBrush software. While colours mixed, the geometrical matter that constitutes the photorealistic 3D model of natural elements and their details disappeared into primitive paint clog that were mixed and brushed again and again into new colours and shapes (Figure 4).

Figure 5 shows examples of both analog brush strokes (top) and digital ones (bottom). The different geometries of these last depend on the movement, pressure and rapidity of mouse. The use of matter with particular radiometric characteristics, such as, for example, the iridescent, the metal or the glossy, highlights the details of brush strokes and creates novel lighting effects.

2.4. RESULTS

The results of these digital manipulations represent an expanded and hybrid nature whose depictions collapses reality and artifice and meanwhile insinuates that contemporary materials are often a mutation from the “original”, producing a world in which fact, fiction and fantasy co-exist.

Figure 2. Example of hyper-realistic reproduction of natural elements.

Figure 3. Example of transition from the hyper-realistic representation to the addition of painting effects.

Figure 4. Transition from a reality-based 3D model to new geometries and colours obtained using digital 3D brushes. Through the simulation of liquid paint, the detailed polygonal meshes are transformed into primitive paint clog.

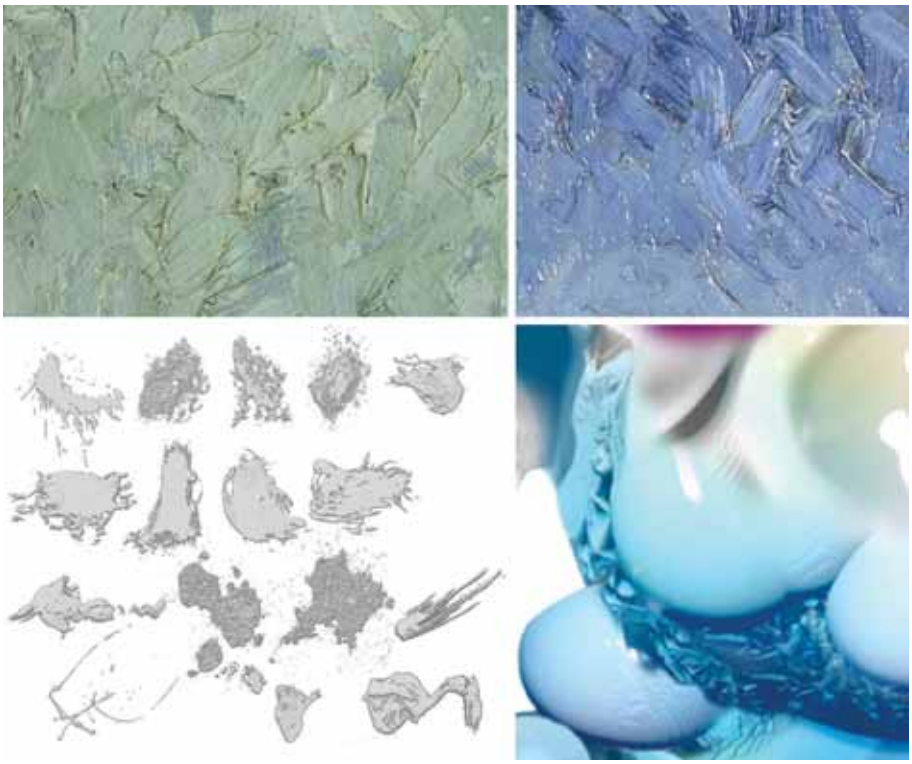

Figure 5. Examples of analog (top) and digital 3D brush strokes (bottom).

Figure 6. Example of transition from hyper-realistic 3D modeling of natural elements to the manipulated one using 3D painting effects. This synthetic manipulation was expressively designed to be used in an architectural context.

Ideas about nature and its simulation are central to the present project, inviting the viewer to question what is "real" and what is not. Such depictions do not yield to clean judgments or bottom lines, especially not about what is living or non-living, organic or technological, promising or threatening, true or synthetic. As a matter of fact the boundary between true and artificial has become even more blurred since digital processes became sophisticated in hiding their procedures.

Even though these manipulations are made by relentlessly computational methods of production like 3D laser scanning of real objects, computer software like ZBrush and industrial fabrication procedures, like printing on vinyl, this project plays both sides of the argument between the machine and the hand. The materiality of the paint becomes the medium where both digital and analogue can be displayed as coexistent: the brush strokes of tempera (obtained by the click of a mouse on a flat screen) portray the gesture of the artist and prove themselves effective in insinuating the idea in the viewers that the paint was once fresh, sticky and was indeed brushed.

As a result, within the present project, manipulated nature becomes a synthetic matter that can be used, for example, within architectural contexts through the use of digital fabrication technologies. Figure 6 represents an application of these manipulations to architectural interior walls and floors.

3. Remarks and Conclusion

The present project investigates how the recent advancements in the digital technologies field are providing new tools for representing ideas in a more direct and intuitive way. As a matter of fact, for example, the possibility to carefully reproduce a human gesture and therefore act in a digital environment is becoming even more refined and similar to analogue behaviours.

In addition, during the last two decades, scientific research is constantly developing new algorithms able to improve the representation of reality mediated by the senses.

Moreover, since digital technologies have provided sophisticated instruments able to acquire the geometric and radiometric characteristics of real 3D objects and scenes and restore hyper-realistic reconstructions, the request of representation abilities in the faithful reproduction of reality can be fulfilled by specific skills in the use of calculation algorithms integrated in 3d modeling software. As a consequence, since digital tools have widened the range of matter with different geometric, chromatic, luminance and weather characteristics able to give consistency to 3d models and scenes and actually allow the imitation of different painting techniques, the "Tempera" project transposes the language renewal of the impressionist movement in the 3D digital context and represents an example of a

new iconographic repertoire able to create novel atmospheric and chromatic effects.

References

Adhemar, H. and Clark, A. M. (eds.): 1974, *Centenaire de l'Impressionnisme*, Secrétariat d'Etat à la Culture, Paris.

Baran, I., Schmid, J., Siegrist, T., Gross, M. and Sumner, R.: 2011, Mixed-Order Compositing for 3D Paintings: Proceedings of ACM SIGGRAPH Asia, *ACM Transactions on Graphics*, **30**(6), 132:1–132:6.

Bernardini, F. and Rushmeier, H.: 2002, The 3D Model Acquisition Pipeline, *Computer Graphics Forum*, **21**(2), 149–172.

Blais, F.: 2004, Review of 20 Years of Range Sensor Development, *Journal of Electronic Imaging*, **13**(1), 231–240.

Büchner, L.: 1864, *Force and Matter: empirico-philosophical studies, intelligibly rendered*, Trubner, London.

Daniels, E., Lappas, A., Katanics, G.T: 2001, *Methods and apparatus for three-dimensional painting*, US Patent 6,268,861 B1.

Guidi, G. and Remondino F.: 2012, 3D Modelling from Real Data, *in* C. Alexandru (ed.), *Modeling and Simulation in Engineering*, InTech, 69–102.

Janet, P.: 1866, *The Materialism of the Present Day, a Critique of Dr. Büchner's System*, H. Bailliére, London.

Le Bon, G.: 1905, *L'Evolution de la Matière*, Ernest Flammarion, Paris.

Lohr, U., Beraldin, J.-A. and Blais, F.: 2010, Three Dimensional Laser Scanning Technology, *in* G. Vosselman and M. Hans-Gerd (eds.), *Airborne and Terrestrial Laser Scanning*, Taylor & Francis.

Manferdini E. and Manferdini A.M.: 2011, Synthetic. *Integration through Computation: Proceedings of the 31th Annual Conference of the Association for Computer Aided Design in Architecture ACADIA 2011*, Association for Computer Aided Design in Architecture, 66–71.

Meier, B.J.: 1996, Painterly rendering for animation, *Proceedings of the 23rd annual conference on Computer graphics and interactive techniques*, 477–484.

Moffett, C. S.: 1986, *The New Painting. Impressionism: 1874-1886*, Fine Arts Museums of San Francisco, National Gallery of Art.

Newton, I.: 1704, *Opticks*, Smith&Walford, London.

Wang, C.-C. (ed.): 2011, *Laser Scanning, Theory and Applications*, InTech.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 893–902. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

INVESTIGATIONS ON QUADRILATERAL PATTERNS FOR RIGID FOLDING STRUCTURES

Folding strategies – rigid and curved folding

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Abstract. A rigid spatial structure represents a three-dimensional structural system in which the size of the singular planar elements is very small related to the whole construction. In this paper we will do investigations of quadrilateral patterns and we will propose an analytical method for designing structural rigid folding with quadrilateral patterns following geometrical surfaces of different topology. Our method offers folding structures with four fold lines meeting in one node which allows a simpler solution of join connections and assembling of the whole spatial and structural system. As the physical characteristics of paper can lead to all kinds of wrong conclusions it is necessary to use CAD tools in addition to scale models, where the entire folding element is reconstructed and its geometric characteristics are controlled. This kind of control reflects on the scale model. Models are then adjusted, examined and built to reach certain conclusions that are once more tested in CAD software.

Keywords. Rigid and curved folding; quadrilateral folding pattern.

1. Introduction

In the field of origami it is investigated how to design different shapes only from one sheet of paper using folding techniques. In the folding technique single planar material is folded without stretching, tearing or cutting. This theoretical definition of folding technique exists only in geometrical and mathematical context using ideal zero-thickness. If we consider material thickness and stiffness for large scale space structures, stretching and tearing inevitably appear in the construction. We start our research with the three basic origami patterns Yoshimura Pattern, Diagonal pattern and Muira Ori pattern in order to find

geometrical properties according to the load, stiffness and stability that we can use as a pattern in architectural context. Our approach is not making classical kinetic foldable structures but to use geometrical principles and static advantages of modular and tessellated origami in order to classify quadrilateral folding structures and develop interactive methods for designing structural rigid folding with a load-bearing effect for topologically different geometrical structures with quadrilateral patterns.

The theoretical basis for our research is funded in geometrical and mathematical properties of classical origami (Belcastro and Hull, 2002a, 2002b; Nojima, 2002; Tachi, 2009) and in applied research of folding plate structures made out of cross-laminated timber panels (Buri, 2010; Haasis and Weinand, 2008). Our research differs from previous research in that way that it is based on tessellated origami. We use analytical methods to define quadrilateral patterns in rigid folding structures for topologically different surfaces.

2. Practice and Application

In architectural terminology, the term folding structures stands for structures consisting of polygonal elements. Their main characteristic is that individual polygonal elements are very small in size compared to the scale of the entire structure's bearing capacity.

Folding structures are found in many fields, such as industrial design, fashion, interior design, architecture, textile industry and jewellery. They can be made out of different types of material, such as paper, textiles, cardboard, wood or metal. Literature dealing with this topic can be divided into three groups. The first group is written for designers (Jackson, 2011). The second group analyses folding structures and principles from the mathematical point of view (Kawasaki, 1989; Mitani, 2009; Miyazaki et al., 1996; Nojima, 2002; Zimmer et al., 2012). The third group deals with practical applications. It analyses the static and dynamic characteristics of folding structures, taking into account the type and thickness of materials of which they are made (Tachi, 2011). There also exists a software package offering an origami simulator (Tachi, 2012).

3. Folding Structures

Rigid folding structures are three-dimensional structures. They are built by folding planar materials while keeping all the elements planar after folding. Curved folding structures are built by folding a single curved surface so that the resulting structures consists of single curved elements as well (Figure 1).

Figure 1. Rigid and curved folding structures.

4. Intuitive Folding

Folding techniques are a field often explored with "learning by doing" methods. The work on these structures begins with simple paper folding, playing with paper and using the simplest drawing materials. Many different forms are produced in a short time, intuitively and easily. If these structures are made of paper, which allows further bending, then the simplest folding patterns can produce many different forms. Figure 2 shows a cross-section of a folding structure and the analysis of possible folding positions within a flexible system of boundary curves. Since it is made of paper, its extreme flexibility is more than obvious.

The physical characteristics of paper can lead to all kinds of wrong conclusions. For example, paper is easy to twist out of its plane, thus changing the position of the entire three-dimensional structure. Hence, the folding structure surfaces shown in Figure 2 do not consist of planar elements, that is, they are not rigid structures. It is therefore necessary to use CAD tools in addition to scale models, where the entire folding element is reconstructed and its geometric characteristics are controlled.

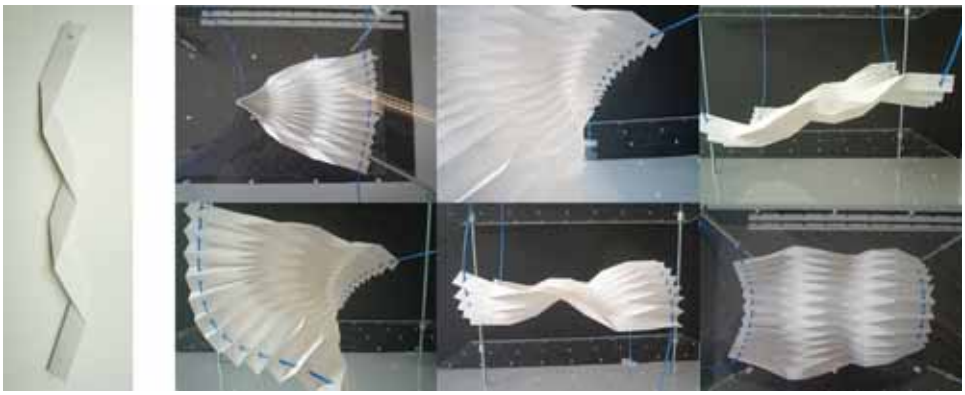

Figure 2. A cross section (left), its folding and numerous analyses of the form.

This kind of control reflects on the scale model. Models are then adjusted, examined and built to reach certain conclusions that are once more tested in CAD software.

One of the most useful methods is defining parametric models. The biggest advantage of parametric models is that, depending on the form of objects, they provide a direct connection to the folding pattern. Yet another advantage is the possibility to simulate dynamic models by opening the structure, starting from the open position (sheet of paper) to the complete folding into a single strip.

To be able to model complex structures and generate patterns, one needs to understand the theory of folding. This includes knowledge of basic patterns, folding methods and understanding of spatial transformations in the folding process.

5. Basic Folding Patterns

Folding patterns are based on lines (rigid folding) or curves (curved folding) and on a two-dimensional material which is folded to make a three-dimensional structure. Folding produces lines or curves which alternate in mountain and valley folds.

Among many types of folding patterns, architects are particularly interested in the Diamond Pattern, Diagonal Pattern and Miura Ori Pattern, especially their design and structural aspects. Rigid folding structures are based on these patterns. Their significance is reflected in the following:

- They give structural stability to three-dimensional forms;
- Basic pattern can be modified, achieving remarkable variability;
- Different patterns can be combined;
- They are the basis for the development of curved folding patterns.

5.1. DIAMOND PATTERN (YOSHIMURA PATTERN)

This pattern was named after the Japanese scientist Yoshimura who observed the behaviour of thin cylinders folded under axial compression force (Miura, 1969). He found out that the surface folds of a folded cylinder follow a specific pattern which is similar to a diamond (Figure 3). The base for this pattern is a deltoid that

Figure 3. A cylinder and its folding patterns consisting of triangles and trapezoids.

Figure 4. Diagonal Pattern as a result of cylinder torsion.

is folded along a diagonal. Deltoid edges are folded as a mountain fold, while one diagonal is a valley fold.

A variant of this pattern can be produced if the deltoid structure is stretched following one diagonal, thus becoming a hexagonal form (Figure 4 center). In this case, instead of getting triangles we get two symmetrical trapezoids. With diamond pattern folding, all diagonals define polylines which approximate the cross sections of the cylinders.

5.2. DIAGONAL PATTERN

Diagonal Pattern is very similar to the Diamond Pattern. This pattern is achieved when torsion is applied to a folded rotational cylinder (Figure 4).

The basis of this pattern is a parallelogram, folded along its diagonal. All diagonals define the valley fold, while all parallels define the mountain fold. With the Diagonal Pattern, in contrast to the Diamond Pattern, diagonal lines define helical polygonal lines, used to define helical folding structures.

5.3. MIURA-ORI PATTERN (HERRINGBONE PATTERN)

This pattern was named after the Japanese scientist Miura who used this spatial structure system to make kinetic solar systems in space. This pattern consists of symmetric parallelograms forming in two directions a zigzag configuration (Figure 5).

Figure 5. Miura-Ori pattern.

This configuration allows the opening of patterns in two directions. A variation of this pattern is reflected in the transformation of the parallelograms into trapezoids, which enables fabrication of concave or convex folding structures.

In architectural terms, it is very important to continue with the development of these three basic patterns to produce new variations of the form. This kind of research can be divided into two trends. The first one involves the study of variations in relation to basic 2D patterns which in return generates new patterns. The second trend starts from an already known 3D shape, as a basis for the construction of the folding structure. The first step to understand pattern generation is to study the basic folding techniques.

6. Basic Techniques

Fabrication of three-dimensional folding structures involves two dominant techniques: parallel folds and reverse folds.

With parallel fold technique paper is folded along the lines generating alternating valley and mountain lines (for example Figure 3 and 4 right). Reverse folding technique changes the direction of basic folding (Figure 6).

After folding around the diagonal d, the mountain fold a turns into the valley fold b. In this way two planes become four, meeting in point A. The position of the diagonal d affects the change of folding direction.

Figure 6b shows the reverse folding as a geometric transformation of a 3D reflection about a plane α. The plane α is defined by the diagonal d and it is perpendicular to the vertical plane β which is symmetric to the parallel folding. Figure 6c shows a part of the structure with the belonging folding pattern (Figure 6d).

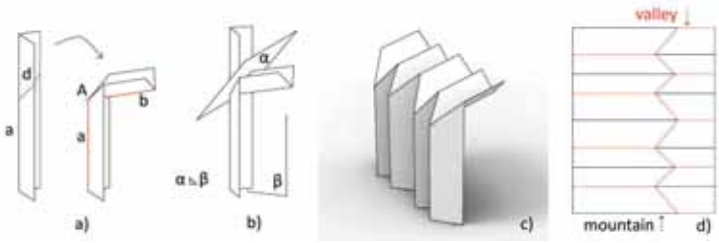

Figure 6. Reverse folding with reflection on the plane α.

7. Grid Generation Analyses

In our analysis we consider cylindrical shapes, based on a modified diamond pattern. As we have seen from basic patterns, the folding structure pattern is

composed of a series of polygonal or triangular elements. When these elements are folded, they take specific positions in space so that two adjacent elements meet along a single line, while several elements meet in a common point. If the folding structure is composed of triangular elements, then a single point can be the meeting point of six or more adjacent polygons. If we assume that such structures are made in real scale (with appropriate material thickness) it can be very complex to calculate and implement the intersection point of a number of different polygons. That is why we have chosen pattern configurations consisting of trapezoids and representing a modified diamond pattern. The advantage of this pattern, compared to the triangular structure, is that at one common point "only" four planes meet.

Figure 7 shows the whole process of the folding structure generation, from the original cross-section to the final grid. The convex example shows all the measures used to build the scale model, while the concave example shows the values in general. The starting point for defining a folding structure is its cross-section. It is given in the form of a spline curve. To approximate this curve, we used the curve's control polygon.

For further calculation of folds (Figure 7c) it is necessary to measure the angles formed by each of the lines with the adjacent line of polygons (angle β) and measure the length of segments (a). Based on these angles, it is possible to calculate the folding angle of paper at each point in the polygon:

$$\alpha = (180 - \beta)/2$$

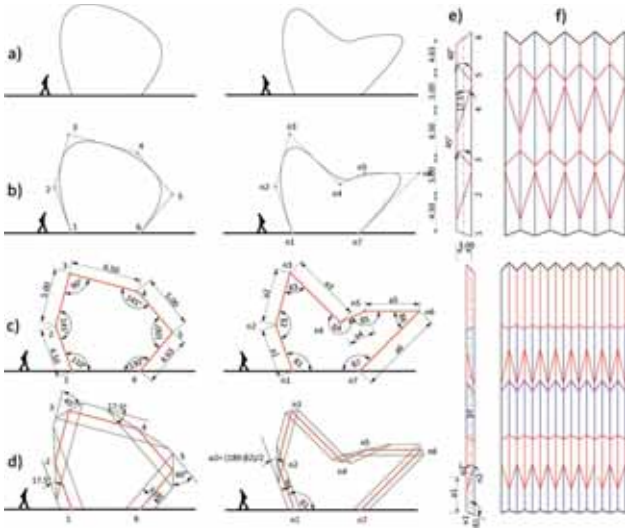

Figure 7. Folding construction and calculation of the folding structure grid.

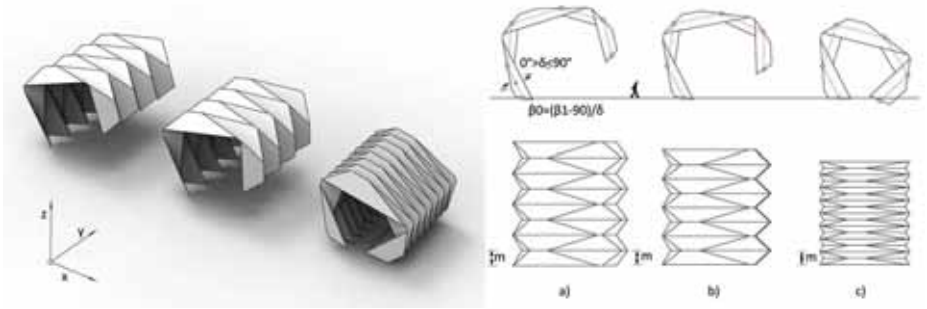

Figure 8. Different opening shapes and folding structure forms.

The distances between the vertices 1–6 of the polygon are distances representing trapezoids centre lines. They define individual structural elements. Parallel to these edges are lines that define the thickness of the folds (Figure 7d). The angle α defines the directions of the two unparallel trapezoid edges.

In convex grids all unparallel trapezoid edges are valley folds. The concave structure grid shows that in the concave part (vertex n4) the trapezoid edge is a mountain fold and it is precisely this point where the structure changes direction from the convex to concave position.

Simulation of paper folding can be done after the grid has been drawn. The entire structure can be folded starting from the flat plane of paper to the maximum folding position, in which the entire structure looks like a folded strip. The structure goes through various stages of folding in this process, thus enabling the generation of many different forms. Figure 8 shows three arbitrary positions of the folding structure.

8. Curved Folding

Reverse folding is a technique that can also be applied to generate curved folding. If one selects a cylindrical surface and then apply reverse folding technique, the result is going to be a curved folding structure (Figure 9). These structures have patterns composed exclusively of curves. Since curved folding structures result from the folding of two-dimensional paper, the resulting surfaces can only be single curved surfaces – cylinders, cones or generalized developable surfaces.

More complex forms of these structures can be achieved if we repeat the primary folding several times. Figure 10 shows some complex cylindrical and conical structures.

If 3D models of rigid and curved folding are generated with 3D software, it is possible to develop a folding pattern of the entire structure directly in software

Figure 9. Application of reverse folding on a cylindrical surface.

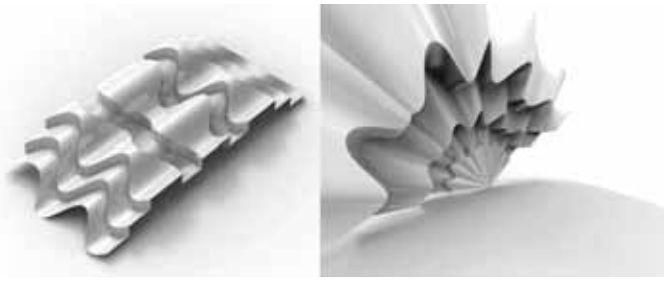

Figure 10. Cylindrical and conical structures – curved folding.

(f. i. Rhinoceros). This is possible because each individual component is a developable surface. Naturally, it must be kept in mind that automated software solutions sometimes contain errors that need to be corrected.

When patterns are first drawn, then 2D drawings are most commonly made in CAD programs. In the process of folding, paper is always folded along two different sides, which results in mountain and valley folds. While drawing, these lines can be marked in different colours, labelling the folding side of paper. Since folding can be complex, engraving the lines on paper (for instance with a laser cutter) helps to accurately and precisely fold the paper along the folding lines. The preparation of such patterns sometimes requires that all the mountain lines are engraved on one side of the material and all the valley lines on the other side.

9. Conclusion

In this paper we investigated geometrical properties of rigid and curved folding. With the help of basic rules of parallel and reverse folding we established a

parametric model for computer aided supported design to generate various steps from pattern generation to folding simulation. The geometrical rules of rigid folding can also be extended to curved folding which we showed on the examples of cylinders and cones.

Future work will be concentrated on parametrically supported folding of various types of surfaces with the aim to generate dynamic architectural elements like shadowing or interactive facade systems using smart materials.

Acknowledgements

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References

Balkcom, D.: 2002, Robotic origami folding, Dissertation, Carnegie Mellon University.

Belcastro S.M. and Hull T.C: 2002, A mathematical model for non-flat origami, *in* T. Hull (ed.), *Origami 3, Proceedings of the 3rd International Meeting of Origami Mathematics*, Science and Education, 39–51.

Belcastro, S. M. and Hull, T.: 2002, Modelling the folding of paper into three dimensions using affine transformations, *Linear Algebra and its Application*, **348**, 273–282.

Buri, H.: 2010, Origami – Folded plate structures, Dissertation, EP Federale de Lausanne.

Haasis, M. and Weinand, Y.: 2008, ORIGAMI – Folded Plate Structures, Engineering, *10th World Conference on Timber Engineering*, Miyazaki, Japan, 2098–2104.

Hunt, W. G. and Ario, I.: 2005, Twist buckling and the foldable cylinder: an exercise in origami, *International Journal of Non-Linear Mechanics*, **40**(6), 833–843.

Jackson, P.: 2011, *Folding Techniques for Designers – From Sheet to Form*, Laurence King.

Kawasaki, T.: 1989, On the relation between mountain-creases and valley creases of a flat origami (abridged English translation), *in* H. Huzita (ed.), *Proceedings of the First International Meeting of Origami Science and Technology*, Ferrara, 229–237.

Mitani, J.: 2009, A Design method for 3d origami based on rotational sweep, *Computer-aided Design and Application*, **6**(1), 69–79.

Miura, K.: 1969, Proposition of pseudo-cylindrical concave polyhedral shells, Institute of Space and Aeronautical Report No. 442, University of Tokyo, 141–163.

Miyazaki, S., Yasuda, T. Yokoi, S. and Toriwaki J.: 1996, An origami playing simulator in the virtual space, *The Journal of Visualization and Computer Animation*, **7**(1), 25–42.

Nojima, T.: 2002, Modelling of folding patterns in flat membranes and cylinders by origami, *JSME International Journal Series C*, **45**(1), 364–370.

Tachi, T: 2009, Generalization of Rigid-Foldable Quadrilateral-Mesh Origami, *Journal of the International Association for Shell and Spatial Structures*, **50**(3), 173–179.

Tachi, T.: 2011, Rigid-Foldable Thick Origami, *in* P. Wang-Iverson, R. J. Lang and M. Yim, (Eds.), *Origami 5: Fifth International Meeting of Origami Science Mathematics and Education*, Taylor & Francis, 253–264.

Tachi, T: 2012, "Freeform origami". Available from: Open Source Repository <http://www.tsg.ne.jp/TT/software/#ffo> (accessed 8 December 2012).

Zimmer, H., Campen, M., Bommes, D. and Kobbelt, L.: 2012, Rationalization of triangle-based point-folding structures, *Computer Graphics Forum*, **31**(2), 611–620.

RESPONSIVE ARCHITECTURE

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ALOPS CONSTRUCTIVE SYSTEMS

Towards the design and fabrication of unsupervised learning construction systems

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Abstract. In this paper we explore the concept and design guidelines for an Autonomous Learning Oriented Proto System (ALOPS), a construction system designed to enhance its own performance through time. Our research has been focused on the fabrication of a prototype for a porous wall system which reacts to light intensities by closing or opening its apertures. Taking that aim, we used a combination of robotics, programing, and material behaviour to endow the system with the capacity to record reactions towards encountered sets of conditions during its active energy periods, allowing the system to use this knowledge database to evolve autonomously by feeding this information back into the computation process. This approach in construction systems opens up the architectural design processes to address the creation of digital memory structures rather than complex algorithms in order to operate specific functions. With this development, the architect could think of architectures constantly evolving by learning from their environments as well as of users forming symbiotic and behavioural bonds with the emergent spatial personalities, thus affecting the underpinning relationships between architecture, user and context.

Keywords. Performance architecture; unsupervised learning; machine learning.

1. Introduction

For the last year (2012) we were working to generate an art piece related to architecture. Our first approach looked at the fabrication of a responsive surface that reacts to light intensities to open or close its apertures; we referred to this prototype as a ‘proto-membrane’ due its main function of controlling the light exchange from one side of the surface to the other. As the project moved forward we faced decisions that shaped and changed the direction of our research, from selecting a

solar power source to feed the prototype and no batteries appealing to an unplugged performance, and the use of softer and flexible materials for actuation to the recording of the information encountered by the system.

Questions like "What kind of information can we save?" or "What for?" Started conversations about how spatial performance could be affected if we included this recorded information in the computation process. Upon further research we came across the field of machine learning and to be more specific the unsupervised learning methods. These concepts seemed to fit somehow with some of the latest descriptions of how performance in architecture works.

The current paper is divided in three main sections in the first part will address the performative paradigm and unsupervised learning techniques defining a theoretical and practical ground upon which the concept of ALOPS is based. In the second part we talk about our experience working with these types of systems through the description of their components and the design challenges that were presented. The third part will revise the design process and capture the different creative activities in which we incurred throughout the development of the first prototype.

2. Contextualization

The incursion of robotics and cybernetics in the field of architecture has been around for several decades, attempting to portray the notion of a moving, responsive and adaptable space. These attempts have generated a conversation in the theoretical discourse of the architectural field finding a niche in the performative paradigm; moreover the attempts themselves remain as samples of the different approaches to this intersection as well as their flaws and achievements.

2.1. CONCEPTS OF PERFORMANCE IN ARCHITECTURE

In the theoretical discourse of "Performance in Architecture" we have witnessed the two main approaches in which this term has been used. From Performativity as a form of representation leading buildings and spaces to attempt the representation and interpretation of different characters falling into symbolic designs used in the first incursions of the performative turn in the 1940s and 1950s, to the use of performance merely as a synonym for function. These definitions suffered from crucial disadvantages coping with a fast changing society and technologies hence we will not use them for the purpose of this paper.

In recent years the concept of architectural performance has been expanded by Michael Hensel (2010), defining it as a multi-agent network of relationships that result in a broader range of possibilities for spatial performances considering four main agents as components of this network: the subject, the environment, spatial

organization and material organization. We will adopt this notion of multiple forces shaping the performance of architecture which introduces a new state in the relationship of form and function, where form becomes a result of the interaction and communication between the agents, and specific functions are demanded by the nature of their relationships. Although the concept of performative architecture proposed by Hensel relies on a biological paradigm making many interpretations fall into bio-representation and performance choreography, we will use the new concepts of multiple interaction as a definition of performance to work as a theoretical base on which our research stands.

2.2. PERFORMATIVE DESIGN PRECEDENTS

When it comes to the actual spatial performances accomplished via construction we take as a first reference Jean Nouvel's Museum of the Arabic world 1981; in this famous (or to some infamous) design, the building's façade was inspired by the traditional Arabic apertures that filter the intense light of the environment, this exterior treatment was embedded with a mechanism to open or close the apertures controlling dynamically the amount of light entering the space. The relevance of this building, whether or not it was a successful endeavour, resides in its attempt to include a certain performance where the building's aesthetics express different effects while responding to information obtained from the environment, achieving a first attempt of communication between the agents: environmental and material organisations.

Outside the field of architecture Theo Jansen´s *Strandbeest* dynamic structures 1990, the wind powered skeletons that work between the realms of sculpture and robotics were used to represent artificial life. They also use information and energy from the environment to act as animals, combined with its materiality. Although his structures did not form a spatial enclosure they added dynamism to the ambiance of the context of the beach. The former examples play with environmental forces and start producing performances that convey effectual results on the subject.

When we turn into the subject as an active agent, the BMW Gina concept Car 2008 proposes a new relationship between the functions of the car and the user, where the car reacts to user interaction. Although the concept of interactive controls for a car has been around for several years, Gina's interaction is exponential due the material selected to actuate in front of the user; shifting from hard metallic panels towards the use of flexible textiles the car delivers soft shape transformations that communicate beyond the functional states of the machine.

Perhaps one of the most relevant works that closely relates to what the elements postulated in this paper try to achieve is the *Hylozoic soil* installation by Philip Beesley for the Venice Biennale in 2009. This artificial forest implements a

distributed sensor network driven by dozens of microprocessors, generating waves of reflexive responses to those drawn into its vast array of acrylic fern stalagmites. This referential piece, described as pursuing the physical and functional representation of a biological organism uses global behaviours to choreograph aesthetical performances and it accomplishes several goals desirable by the performative paradigm in architecture; like the luring and continuous stimulation of the subject via the dynamic shifts in shape, material organization as well as it creates a communication network between these elements that results in a spatial defining system whose performance is not specified entirely by the designer.

Taking these works as precedence of a contemporary branch of architectural theory and practice oriented towards the exploration of the performative paradigm including all the concepts that it might entail, our work positions itself recognizing these achievements, adding memory, its structures and information flows as crucial elements in the performative process.

2.3. A GLIMPSE INTO UNSUPERVISED LEARNING

Inside the field of machine learning emerges the Unsupervised Learning approach as an alternative methodology for machines to achieve different objectives. In general terms, the machine is able to recognize certain patterns or structures inside the bulk of input data; since it does not get any error or reward signal when evaluating a potential solution it's said that its learning process becomes unsupervised. There has been a number of different approaches to address the UL processes using purely statistical computation, data mining methods, KDD (Knowledge discovery in data), Clustering, Fuzzy logics, Blind Signal Separation and Neural Networking.

Although the field of UL applied to machine learning has been around for the last half of the XX century there are fundamental questions to be solved. Some issues have been highlighted with their potential approaches for a solution (Hinton et al., 1999). The first issue could be explained with a question: What do we want the system to learn without giving external instruction? Some possibilities are to find clusters in the input data, extract features that characterize the input data more compactly or uncover non-accidental coincidences within the input data.

Another issue was the fact that most unsupervised learning algorithms are based on statistical estimation of the input data. Such algorithms generally suffer with large patterns as the ones produced by the real-world behaviour. In this case computational complexity is an important consideration. Therefore, future investigation on unsupervised learning would need to incorporate appropriate prior structure.

Despite these obstacles, as Andrew Ng pointed out at his conference at Stanford University titled *The future of Robotics and Artificial Intelligence* (2011), machine learning methodologies can help us achieve the bigger Artificial

Intelligence dream of creating machines that can see the world, think, understand and be intelligent the way that people are via neural computation and Unsupervised Learning techniques.

2.4. UNSUPERVISED PERFORMANCE

We will address two problems presented by Unsupervised Learning approach inside the performative paradigm of architecture (using the term of unsupervised performance for these effects). The first problem states an ambiguity of direction where the reason for the system to learn is not clear. In his reading of Umberto Eco`s work, Michael Hensel brings out that:

> Umberto Eco's work invests part of the action in the spectator (Eco, 1989). Such 'open work' is characterised by a deliberate ambiguity of meaning. According to Eco, 'open works' must leave the arrangement of some of their constituents to the public or to chance, thus giving these works a field of possible orders rather than a single definite one (Hensel, 2010).

Bringing the question of performance control down to a matter of balance between control and ambiguity where the designer's directive is needed but does not control the complete performance of the system, letting the other agents to participate in shaping the performative results through time. We will use this approach to include the designer as an influential agent of the system through the establishment of such directives and the system's creative integration.

The second issue addresses a problem of computation overload when systems deal with the real world and its immense amount of information in order to learn from scratch. As a possible solution it states (as the analogy of the new-born baby's brain illustrates) the necessity to take into account previous knowledge gained through its experiences and more important, the communication of this information through different generations to be used as a source of knowledge. Our approach investigates the possibility to endow constructive systems with the ability to digitally record and communicate information relevant to the directive stipulated by the designer through generations marked by active or inactive periods of energy in the system. Heading towards a performance that includes both the different agents before mentioned in the performative results and the information stored from previous experiences and previous generations.

3. Elements of ALOPS (Autonomous Learning Oriented Proto-System)

ALOPS (Figure 1) are constituted by two main characteristics: the autonomy or independence from human control and the ability to learn from their own

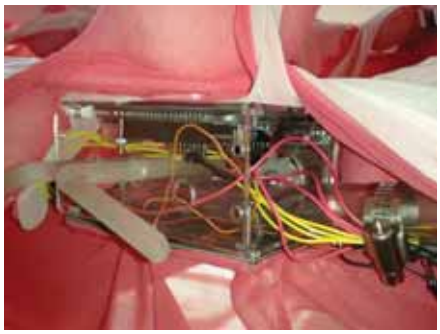

Figure 1. ALOPS prototype internal closeup.

experiences. Independence is needed from the start to unplug the system from different types of infrastructure, de-contextualizing it, making it a free constructive entity with the possibility to be a learning body which also becomes crucial in the adaptation of the system to different environments, users and other constructive systems.

3.1. SYSTEM HARDWARE COMPONENTS

The physical composition of the system forms a multi-layered arrange of elements that communicate geometrically and digitally between each other. We will start our description from the structural component which in this case serves not only as a chassis for the system but also as the generator of geometrical communication possibilities between the components that are arranged throughout and within it. The next two layers going inwards consist of the Digital Memory and Processing Units, in charge of performing all the digital control of the system, such important tasks take advantage of the structural component arrangement to get protected.

The other three layers described in (Figure 2) as going on top of the structural component are the interfacing components of the system consisting of an Actuation System transforming instructions and energy into movement, Material Communication expressing these adaptations with the desired aesthetical coordination, and an Energy Supply/Sensibility component in charge of gathering information from the environment as well as the necessary energy to perform the required processes. Let us remember that the layering rendered in (Figure 2) does not imply a geometrical superposition of elements as they can be weaved, attached or arranged in different ways, in this case the diagram focuses on the geometrical and digital communication between these physical components.

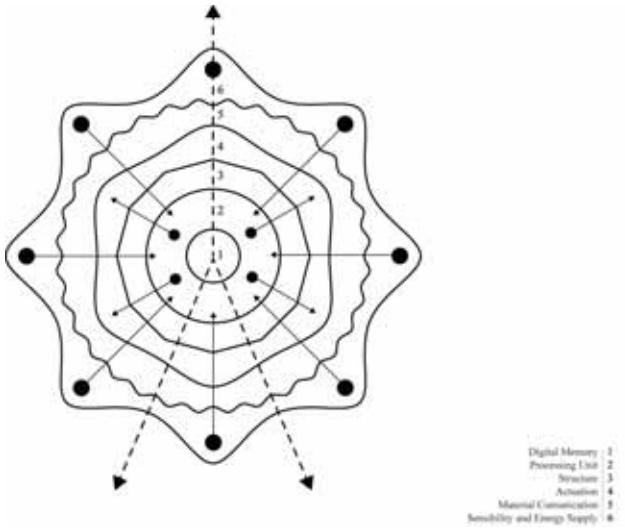

Figure 2. Hardware components relationship diagram.

3.2. SOFTWARE MODULES

The flow of information is arranged into an eight shaped feedback loop where the input from the context, designed patterns, and user interaction is collected by an

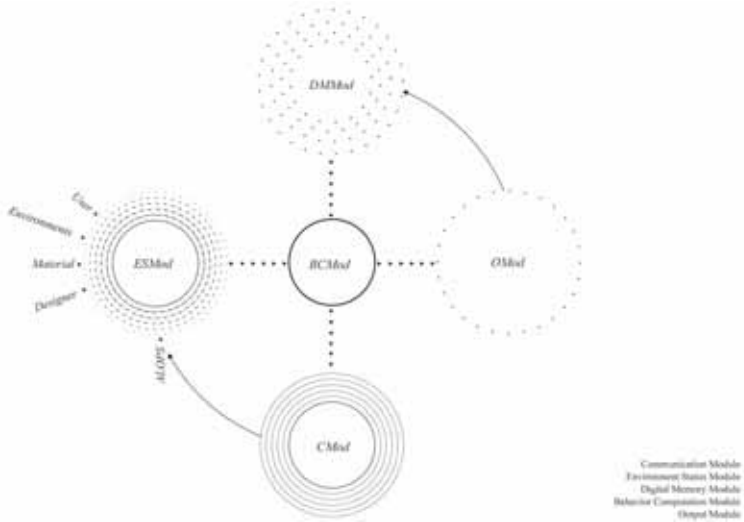

Figure 3. Information flow chart.

Environment Status Module where even the status of other ALOPS is added to have a richer image of the present. At the centre of both loops we find the Behaviour Computation Module in charge of aggregating information stored in the knowledge database to calculate a resulting behaviour according with the proposed directives. That resulting behaviour is then sent to different actuation and communication devices via an Output Module and is also sent to the Digital Memory Module for the recording of the current experience and its addition to the knowledge database; our first prototype used a simple milestone interpolation algorithm to statistically record system status over time.

4. Design

The conceptualization part of the process is crucial, is at this point when we state the primary objectives, the purpose of the system and the functions of the elements that compose it, as well as its overall aesthetical concept, entangled to the spatial qualities you want to achieve. The primary directive can be any function you can think of for a construction system, a motif to consider the design of an ALOPS system in the first place. In this case we used as our main directive the efficient control of solar incidence for an interior space. The secondary directive has to deal with stimuli and self-preservation. Thus the system´s objective is to survive or at least prolong its energy cycles to carry out the primary directive. The third directive will address the evolution of the system, making it transcend through generations via memory transmission.

After defining our aesthetical and functional intentions as well as considering our main directives, we proceed to carry a design method where all the fields are tackled in parallel keeping different systems informing each other and reacting to design changes and decisions. With this approach we also keep the integration of the systems very close not to leave it as a later process. We catalogued the main design activities into the following fields:

- **Creative Perception System**: With very little input you can figure out a lot of information. For example, measuring light intensities we can know about light cycles (time), knowing the number of light cycles we can know how many generations have passed and their average life span, then we can differentiate behaviours in light from cloudy day to a hot summer.
- **Creative Actuation System**: We need to be creative with our actuation systems, nowadays the actuation options have expanded but they are still not as diverse as we would want, besides the energy consumption becomes crucial in the design of this.
- **Creative Learning Mechanisms**: In the field of structuring memory transmission, the quality of the information and the way we store it is of great importance, we already mentioned the different approaches in machine learning to accomplish

Figure 4. Proto-Membrane in exhibition.

unsupervised processes. For the first prototype´s memory structure we used a basic statistical process of saving information data inside a series of milestones obtaining interpolated values to be used in the computation. The algorithm attaches different weights to both direct input and the values obtained from the previous generations to calculate its behaviour, finally an energy threshold is placed so when the system is about to run out of energy, it then records the information stored in the milestones of that ending generation consolidating knowledge preservation.

- **Creative Materiality**: This part of the design process works very close to the actuation system for the sake of minimizing active motion, relying on material properties and behaviours to fulfil the effectual goals.

5. Conclusion and Future Development

The first ALOPS prototype (Figure 4) achieved the system´s reaction to changes in light intensities, and showed certain movements that were clearly not programmed but evidenced reflexes obtained from previous experiences. The materiality, its dynamics even the sound of the actuation mechanisms started communicating different expressions and behaviours to us and without knowing the exact status of the system we started to relate them to happy, playful, sad or anger moments. Currently displayed as part of a multidisciplinary art exhibition, the first ALOPS prototype hangs in a museum room as a sort of robotic taxidermy.

Possible lines of research were found both in the specific design techniques previously described and in the overall coordination of material, perception and actuation by the designer towards an effective characterization of the system. As a next step our research line will look into how the different design activities recognized can be introduced into academic programs. Another direction points towards the issue of evaluating efficiency for specific ALOPS functions when there are uncontrolled variables inside the computation process. Although overall

machine learning field of study is at early stages we visualize different ALOPS being used in buildings for climate control, structural adaptation, dynamic spatial reconfiguration and the production of aesthetical effects.

We can then imagine a space, a building even a city surrounded by ALOPS, where the behaviours of structures materials and other building systems continually evolve and communicate to each other adapting to changes in the environment, different users, and the shifts in the states of other ALOPS. Not only in the computer aided design process will the constructive elements communicate and react but in the physical realm as well. While effectively carrying their functions, they could then start to establish different languages to communicate with us, behavioural languages rich in complexity that directly engage our emotions.

References

Brooks, R.A.: 1991, Intelligence without representation, *Artificial Intelligence* **47**(1), 139–159.
Corbusier, L.: 1946, *Towards a New Architecture*, Architectural Press, London.
Curtis, S. A., Truszkowski, W. F., Rilee, M. L. and Clark, P. E.: 2003, *Ants for the Human Exploration and Development of Space in IEEE Aerospace Conference 2003*, Montana.
Eco, U.: 1989, *The Open Work*, Harvard University Press, Cambridge.
Heackel, E.: 1929, *The Riddle of the Universe*, Thinker's Library, London.
Hensel, M.: 2010, Performance-oriented architecture, *FORMakademisk*, **3**(1), 36–56.
Hensel, M.: 2011, Performance-Oriented Architecture and the Spatial and Material Organisation: Rethinking Definition, Role and Performative Capacity of the Spatial and Material Boundaries of the Built Environment, *FORMakademisk*, **4**(1), 3–23.
Hinton, G., and Sejnowski, T. (eds.): 1999, *Unsupervised Learning: Foundations of Neural Computation*, MIT Press, Cambridge, MA.
Rasmunsen, S., Chen, L., Nilsson M. and Abe, S.: 2003, Bridging Nonliving and Living Matter, *Artificial Life*, **9**(1), 269–316.
Roudavski, S.: 2009, Towards Morphogenesis in Architecture, *International Journal of Architectural Computing*, **7**(3), 345–374.
Weinstock, M.: 2006, Self-Organisation and Material Constructions, *AD*, **76**(1), 34–41.

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INFORMATION STORM

An assessment of Responsive Facades and their potential to introduce new relations between building users and the weather

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Abstract. Today buildings are increasingly responsive to the weather. In such responsive buildings an "Open System" is emerging which consists of a coupling between buildings and their temporal environments. This paper assesses whether these new technologies, in addition to potentially reducing energy consumption, can also lead to a new experiential relation between building users and the weather. The paper qualitatively assesses current examples of Responsive Facades and their effect on the user's experience of the weather. The information structures of the facade systems are then examined. From this analysis identify potential future avenues of research – or strategies – which may be most effective in making the weather apparent. Finally some design proposals which explore the possibilities of these strategies are presented. The paper is intended to complement the current, primarily technical, emphasis of research in this area by exploring the innovative architectural potential of Responsive Facades to create new user experiences and relations to the weather.

Keywords. Responsive facades; weather effects; experience.

1. Weather Information and Responsive Buildings

From the beginnings of its systematic study in the 17th Century Meteorology has always been about the collection and effective use of information (Jankovic, 2001). What this has meant for weather-forecasting is that increasingly vast blocs of information need to be processed and for this reason the fastest computers used today (the so-called supercomputers) are used for this purpose. From this it can be seen that every weather-system contains a huge amount of *non-compressible* information. The relationship between this information and our perception of the weather, through the medium of the responsive facade, is the subject of this paper.

Today buildings need to be able to adapt to changing conditions outside in order to maintain the effective running of heating and/or cooling systems inside (Perino, 2008). It could be said that in such responsive buildings an "Open System" is emerging which consists of a coupling between buildings and their temporal environments. The result is a continuous free-flow of constantly-changing information from the weather to buildings and back again (see for example Knaack et al. (2008) and Ritter (2007)).

Historically the design of energy-efficient buildings has sidestepped the potentially insuperable complexity of this relationship by being solely based on *climatic* information. The rich and varied information of the weather has been compressed into long-term statistical averages removing the unpredictable variability of actual temporal change and replacing it with seasonal means. But today, the limits of this approach are being reached. While buildings can become more energy-efficient this also means that they are more sensitive to deviations from the predicted climate (van der Aa et al., 2010, pp. 112–113).

On the other hand, while energy is becoming more and more expensive -both monetarily and environmentally —and this is likely to continue into the future (DGEE-IEA, 2012 p. 3)— we also have the imminent arrival of the so-called "Internet of Things" (Guo et al., 2011). These two developments together mean that the costs of installing, running and maintaining responsive buildings will decrease and, increasingly, be offset by the savings in energy consumed. This leads us to believe that, even though there have been some issues with the spread of responsive buildings (Perino, 2008, pp. 24–25), they are likely to become more common and inevitably more sophisticated in the future.

2. Responsive Facades

In this paper we are discussing what have been variously called Advanced Integrated Facades (AIF) (Perino, 2008) or Climate Adaptive Building Shells (CABS) (de Boer et al., 2011). Here we use the term Responsive Facades (not to introduce yet another term but because we feel this is more inclusive of all the examples we look at-not all examples can be described as "Advanced", it omits the overt reference to Climate in CABS and also it is less cumbersome).

Our definition of a Responsive Facade is: A facade that responds automatically to variations in external and/or internal environmental conditions, in order to reduce the energy consumption of a building.

It is clear that the complexities of the responsive building envelope require much technical research. While acknowledging the importance of this work, this paper takes a more qualitative approach. We also take a different track to previous qualitative analyses such as Wyckmans (2005) and Loonen (2010) by assessing how the *user's experience* of these envelope systems can create new relations

between users and the weather by taking in the information generated by the weather and not just displaying it but making its dynamic apparent through the performance of the envelope.

3. Analysis

Methodology: Thirty new and existing Responsive Façade Technologies were selected and analysed against a series of criteria outlined below (see Table 1). Each technology was assessed empirically for its ability to produce effects which would make the dynamic of the weather apparent. This assessment took a phenomenological approach based on empirical evidence: personal experience, video documentation and extrapolation from written descriptions, following the model of phenomenological research in environmental design proposed by Seamon (2000).

Weather in the environment is sensed through vision (clouds, sunlight, snow etc.), thermoception (the sense of heat), sound (the wind blowing, thunder etc.), touch (wind or rain against the body) and even smell (the smell following rain is

Table 1. Matrix of Responsive Façade Technologies against selected criteria.

	CABS Name	**Conventional technologies**	1. Le Corbusier's mur neutralisant	2. Modern Double Façade Systems	**New Materials:**	3. Electrochromic glazing	4. Photo-chromic glazing	5. Photoelectrochromic glazing	6. Gasochromic glazing	7. Fluidized Glass Façade	8. GlassX crystal -(wax PCM)	**New Components**	9. Adaptive Fritting	10. Integrated Venetian blinds	11. Printed ETFE foil cushions	12. Glazed louvres	13. The esplanade -Singapore	14. Aegis Hyposurface	15. Aldar Central Market	16. Institute du Monde Arabe	17. City of justice, Madrid	18. Flare façade	19. SmartScreen (shape memory)	20. Hotel habitat Ruiz-Geli	21. Kinetic light	22. GSW Berlin	23. Bremtex, VOX Architects	24. Solar shutters (TU Graz)	25. PV shutters (Colt International)	26. Deployable External Insulation	27. Heliostat	28. iHomeLab	29. Sagami bay house -Foster	30. Showroom Kiefer technic
	Visible ?					■	■	■	■	■	■		■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Type of Visible Response	A. Position												■	■	■	■	■	■	■	■	■					■	■	■	■	■	■	■	■	■
	B. Shape																					■	■											
	C. Colour					■	■	■	■	■	■																							
	D. Data																							■	■									
Speed	A. Instant					■	■	■										■								■								■
	B. Delayed								■	■			■		■		■		■	■	■	■	■	■	■		■	■	■		■	■		
	C. Deferred										■																			■				
Scale	Microscopic					■	■	■	■	■	■																							
	Component												■	■	■	■	■	■	■	■	■	■	■	■	■	■								
	Object																									■	■	■	■	■	■	■	■	■
Inform. Structure	Open		■				■	■			■			■		■							■				■	■	■					
	Closed			■		■		■	■	■			■	■	■		■	■	■	■	■	■		■	■	■	■				■	■	■	■

quite different to before). Vision, however, is clearly the way in which architecture is most commonly described (drawings, models, simulations etc.) and, inevitably, experienced. We do live in a visual culture after all (Jay, 1994, pp. 21-82) and, for this reason, we will focus in this paper on the potential for Responsive Facades to create a *visual* link to the usually invisible dynamics of the weather.

In addition, to be perceptible, a change in the weather must be visible at a *speed* we can perceive -fast-approaching rain clouds can be seen moving towards us but the clouds of a slow-moving pressure-system cannot. And it must be at a *scale* where we can perceive difference between different areas -a large mass of cloud that fills the sky from horizon to horizon may be moving or changing but this will not be immediately visible while the drift of small, moving clouds is much more easily perceivable. Based on this analysis of how the weather is perceptible in nature, we identify 3 criteria which are required for a facade system to make the dynamics of the weather perceivable: Visibility, Speed, and Scale. Under each criteria we identify varieties of performance. We then assess the potential effectiveness of the different varieties of performance to give a perceptual link to the weather.

3.1. VISIBILITY

First it must be determined if the performance of the responsive building envelope visible, and if so, is it visible at the macro scale to human observers? This criteria separates the many responsive building technologies that have no visible effect, such as conventional double facades, concealed ventilation etc., from those which do. We identify several ways in which changes in the weather are made perceptually visible:

- **A. Changing Position:** Through the adjustment of shading in response to the changing position and intensity of the sun (Responsive Shading). This can take the form of mechanical devices such as shutters, louvres etc. Examples include the "Solar Shutters" as used on the Biokatalyse building at TU Graz (Wyckmans, 2005, p. 165) or the Glazed Louvres used on the LVA Schwaben Building, Augsburg (Wyckmans, 2005, p. 170).
- **B. Changing Shape:** Through the visible effects of changing shape as a result of an environmental change or stimulus. For instance flexible materials which move in the wind; laminates with different expansion rates bending in response to heat. One example would be the prototype Homeostatic Facade System developed by Decker Yeadon (deckeryeadon.com).
- **C. Changing Colour or Opacity:** Through a change in the visible appearance of a material as a result of an environmental change or stimulus (Responsive Materials). Examples include Electrochromic, Photochromic and Gasochromic materials; Phase-Change Materials (PCMs) etc.

- **D. Data Visualization:** the translation of invisible data (temperature, wind speed, humidity) into visible stimulus -digital readouts, colour gradients etc. Examples include Hotel Habitat by Ruiz-Geli (Ritter, 2007, p. 128) or Kinetic Light (Loonen, 2010, p. 51). These are generally "displays" of invisible information streams and, while potentially making the weather visible, they do not contribute to energy saving -in fact quite the opposite.

All four of the visible transformations described above could potentially be configured in such a way as to produce a dynamic effect which reflects the weather if combined effectively with the criteria outlined below.

3.2. SPEED

Selecting those systems that do have a visible effect is that effect at a speed that is immediately perceptible to the human eye? Applying this question to the examples it becomes apparent that the visible effects can be separated into 3 speeds of performance:

- **A. Instant** – visible change (within seconds) in the appearance of the facade as a result of changes in input. For instance the change in colour of electrochromic glass as a result of changing input voltage.
- **B. Delayed** – a change in appearance that is directly attributable to a change in weather conditions but which happens some time later (usually in the range of 10 seconds to several minutes). A typical example would be the change in colour of photochromic glass, as a result of changing light levels which can take from several seconds up to 1 or 2 minutes.
- **C. Deferred** – a change in the appearance of the facade which takes place several hours after a change in ambient conditions. A typical example of this would be the day-to-night transformation in a phase change material facade. Example: GlassX Crystal PCM (Ritter, 2007, p. 164).

We suggest that in order to register most clearly with people's experience of the weather a transformation in the facade should be as fast as possible.

3.3. SCALE

If the effect is immediately perceptible at what Scale does the visible change take place? Here again we have 3 categories:

- **A. Microscopic:** Some transformations take place at the microscopic scale and therefore appear uniform to the human eye. For example electrochromic glass that changes colour all at the same time.
- **B. Component-scale:** This is the transformation of visible components which are small enough not to be discernible as individual objects combining instead into a distributed field effect.

- **C. Object-scale:** At this scale responsive building elements are large enough to be comprehended as individual objects-eg. shutters, louvres etc.

The distinction between B and C is not absolute and is related to the overall scale of the building. For instance storey-high shutters on a small building of 2-3 storeys will appear as distinct objects (Example Biokatalyse building at TU Graz (Wyckmans, 2005, p. 165) while on a large building of many storeys they will appear like a distributed field as seen in the GSW Building by Sauerbruch Hutton (Sauerbruch et al., 2000, and the author's personal experience). In addition detail, colour etc. can concentrate or dilute this effect.

In terms of implementation the Component Scale is, in most cases, probably the most complex/expensive. However it is the most sensitive to local variation and so can potentially provide the most finely adjusted energy savings and so these systems are likely to become more common. In addition simplifying the complexity of the individual component and especially its mechanics can reduce the overall complexity and cost.

3.4. INFORMATION STRUCTURE (OPEN OR CLOSED)

As mentioned at the beginning of the paper information intensity and non-compressibility is one of the distinctive characteristics of the weather thus we also look at the way in which information is processed. Loonen (2010) provides a useful distinction in this regard between "Closed Loop Control" and "Open Loop Control". To summarize his categories:

An Open Loop Control System (OLCS) is one where there is a direct transformation of the system or component as a result of changing conditions. Examples of this would be photochromic or thermochromic glass and phase change materials (PCMs) where material change happens without the need for any remote data processing. The disadvantages are that it's performance is hard to predict and if not anticipated correctly at the design stage it can be problematic as its performance cannot be changed.

In a Closed Loop Control System (CLCS) on the other hand information is taken in (via sensors) processed (digitally) and instructions are output (to materials or actuators). CLCS is more complex but has advantages: the use of feedback; potentially the ability to "learn" over time; and the possibility of human intervention to adjust the parameters, used to control response.

The question we are interested in here is: Does the type of control system influence the potential relations between the weather and the building?

In this regard OLCS has the advantages that, because of its relative simplicity, it can be fast and it can be the cheapest way to get the immediate effect required.

The advantages of CLCS are that the software can be adjusted after installation-either through human input or the system, if programmed to do so, can "learn" and optimize its responses. This suggests that both systems have potential but in different contexts-for instance OLCS can provide some environmental control and a direct link to the weather cheaply but cannot be very tightly calibrated to a specific energy performance. The building must have other systems which can make up for energy short-comings. CLCS can potentially provide much more precise responses but can only be installed in buildings where there is a budget and personnel capacity to install and maintain a complex system.

3.5. CONCLUSIONS FROM THE ANALYSIS

Based on this empirical analysis we conclude that for the dynamic effect of the weather to become apparent change must be visible, but this visibility could be a change of position, shape, colour or opacity; It should be instant or delayed only slightly; It should be at a scale where multiple pieces combine into an overall dynamic pattern. In addition, both open and closed control systems have potential if combined with an appropriate material system.

4. Experiments

Based on this analysis, in the experiments presented here, we pursue 2 different strategies:

- Strategy 1: Omit information processing completely and develop a mechanically simple material Open Loop Control System; Compensate for the lower energy efficiency of this kind of system by producing energy.
- Strategy 2: Omit all moving parts but still produce an effect of drift through a Closed Loop System combined with a large (but not too large) number of individual pieces.

4.1. EXPERIMENT 1: "SOLAR GRASS FIELD"

This experiment follows Strategy 1 outlined above, using the wind as the motor driving the dynamic. The experiment began by taking a field of grass billowing in the wind as its model. This performance produces a dynamic effect but it is difficult to align it with any requirement for sun-shading in order to reduce energy consumption (though based on our dynamic simulations it could provide a, statistically, fairly constant level of shading). We address this lack of shading-efficacy by proposing a concept prototype called the "solar blade" which consists of a flexible photovoltaic (PV) material (e.g. Nanosolar (nanosolar.com) mounted on thin

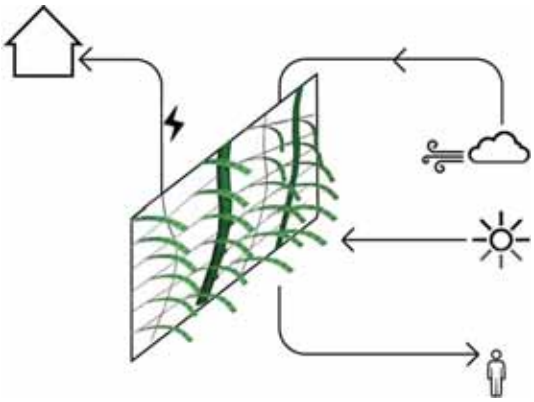

Figure 1. Open Loop System with 2 inputs (wind and sun) and 2 outputs (visual and electric).

metal strips. A relatively recent development, the flexible PV is a fully functional photovoltaic cell mounted on a very thin, flexible sheet of steel or aluminium that allows it to bend while retaining its power-generation capabilities.

The design takes the form of hundreds of these flexible solar blades which are each mounted on a spring which is then attached to a network of lightweight support cables allowing them to bend and flex in the wind. The intention is that the effect would make the weather more apparent by making the local turbulence of the wind visible. The overall performance would emerge from the local interaction of uncompressed climatic information with the specific materiality of the blades (Figure 1).

Outcome: This low-tech Open Loop System has the potential to provide instant manifestation of weather performance in the building fabric however its potential to produce enough energy to offset costs would need to be assessed through prototyping and testing as simulation involving so many parameters (wind dynamics, material flexibility, solar position, overshadowing) is difficult.

4.2. EXPERIMENT 2: "PIXELLATED GLASS FACADE"

Following Strategy 2 this experiment proposes a Closed Loop System that achieves a distributed, responsive field effect with no moving parts. Electrochromic Glass has the advantages that it can respond to changing conditions without the use of moving parts and is, as a result, in comparison to mechanical devices, relatively cheap. But it has the disadvantage, in the context of what we are discussing here, that it gives a uniform instant change from one state to the other. The question this experiment asks is how can we use this material to produce a less uniform, more dynamic effect?

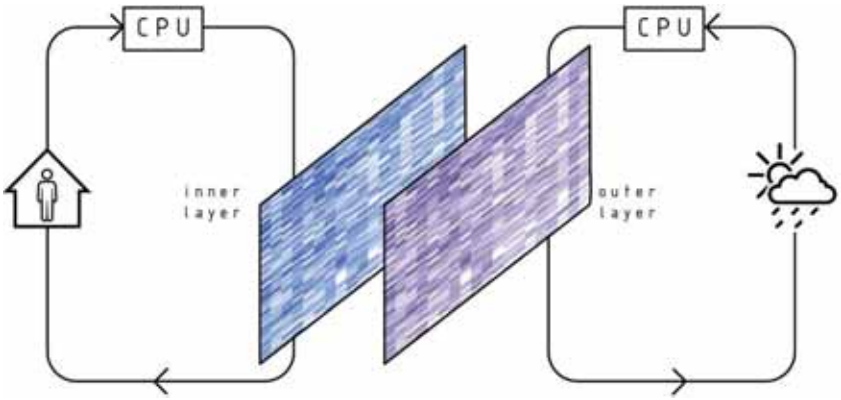

Figure 2. Closed Loop Controls for inner and outer layers of pixelated glass.

To answer this, the concept of pixelization from digital displays is used as a model. Specifically, this experiment proposes the low-resolution monochrome display as a model to translate the changing weather onto the facade while at the same time providing a responsiveness to changing light levels. The pixelated facade would be a curtain wall made up 2 layers of laminated glass each with an electrochromic interlayer, which would be divided into 2,752 pixels (Figure 2). Each pixel would be about the size of the exposed face of a traditional brick and could be individually activated, made transparent or opaque, through the application of an input voltage. Input to the outer layer would be a field of individual sensors or a low-resolution video capture of clouds in the sky, filtered to reflect the overall light level and then pixelated. The inner layer of pixels would be controlled by user.

As clouds roll overhead the facade would adjust its transparency in real time to maintain a constant light level inside while providing an ever-changing display on the outside. The unpredictability of the Weather would introduce an unpredictable element into the facade and its real-time information would be converted directly into a real-time performance.

Outcome: This Closed-Loop pixelated electrochromic system can generate an interesting interaction between the dynamics of the weather on the outside and the of user needs on the inside. Again cost may outweigh energy savings though this would need to be tested through prototyping.

5. Conclusion

In this paper we have described a qualitative analysis of Responsive Facade Technologies to determine their potential to incorporate the perceptual effects of

the weather within the fabric of buildings and hence to make a new perceptual link between users and the weather through the medium of buildings. Our finding is that in order to best reveal the performance of the weather the system's transformations must be visible, instant or only slightly delayed and small-scale relative to the overall scale of the building to produce the dynamic effect of drift. However these requirements would make existing systems quite expensive.

To address this we present two experimental proposals which try to build on the potentials that we have identified by using either materially simple or informationally simple solutions. While, these are only proposals and would need more extensive research and testing to become realizable we hope that they suggest future directions for research exploring the "Open System" which is emerging between buildings, their temporal environments and their users.

References

van der Aa, A., Heiselberg, P. and Perino, M.: 2010, *Designing with responsive building components IEA - ECBCS Annex 44* Aalborg University

de Boer, B., Ruijg, G. J., Bakker, L., Kornaat, W., Zonneveldt, L., Kurvers, S., Alders, N., Raue, A., Hensen, J., Loonen, R. and Trcka, M.: 2011, Energy saving potential of climate adaptive building shells – Inverse modelling of optimal thermal and visual behaviour, *Proceedings of the International Adaptive Architecture Conference*, London, 16.

DGEE-IEA (Directorate of Global Energy Economics of the International Energy Agency): 2012, *World Energy Outlook 2012 Factsheet*.

Guo, B., Zhang, D., and Wang, Z.: 2011, Living with Internet of Things, The Emergence of Embedded Intelligence, *Proceedings of the 4th International Conference on Cyber, Physical and Social Computing,* Dalian.

Jankovic, V.: 2001, *Reading the Skies: A Cultural History of English Weather, 1650-1820*, University Of Chicago Press, Chicago.

Jay, M.: 1994, *Downcast Eyes: Denigration of Vision in 20th-Century French Thought*, University of California Press, Berkeley and Los Angeles.

Knaack, U., Klein, T. and Bilow, M.: 2008, *Imagine 01 – Façades*, 010 Publishers, Rotterdam.

Loonen, R. C. G. M.: 2010, Climate Adaptive Building Shells: What can we simulate? Master's Thesis, TU Eindhoven.

Perino, M. (ed.): 2008, *IEA - ECBCS Annex 44 State of the Art Review: Vol 2A. Responsive Building Elements*, Aalborg University, Aalborg.

Ritter, A.: 2007, *Smart materials in architecture, interior architecture and design*, Birkhäuser Verlag, Basel.

Seamon, D.: 2000, A Way of Seeing People and Place: Phenomenology in Environment-Behavior Research, *in* S. Wapner, J. Demick, T. Yamamoto and H. Minami (eds.), *Theoretical Perspectives in Environment-Behavior Research*, Springer Science + Business Media, New York.

Sauerbruch, M., Hutton, L. and Hartmann, I.: 2000, *GSW Headquarters Berlin: Sauerbruch Hutton Architects,* Lars Müller Publishers, Baden.

Wyckmans, A.: 2005, Intelligent Building Envelopes: Architectural Concept and Applications for Daylighting Quality, Doctoral Thesis, Norwegian University of Science and Technology, Trondheim.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 925–934. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

ECO-MACHINE: A GREEN ROBOTIC ECOSYSTEM FOR SUSTAINABLE ENVIRONMENTS

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Abstract. This paper focuses on developing a kinetic system with responsive solutions for sustainable environments. The emphasis of our work is to develop a zero-energy interactive ecosystem called an "eco-machine". We setup a conceptual framework and investigate how to integrate sensors and actuators into green building tectonics to achieve a sustainable kinetic system. The operational scenario and prototype implementation are reported in this paper.

Keywords. Eco-machine; sustainable environment; interactive architecture.

1. Introduction

There has been an increasing interest in developing interactive architecture that can dynamically alter the physical space in response to changing needs. An interactive architecture system is sought to be achieved by embedded sensors and actuators that continuously interact with the surrounding environment. Research work in interactive architecture has developed embedded sensors or actuators in buildings components that transform its shape and physical properties in response to change (d'Estrée Sterk, 2005; Oosterhuis and Biloria, 2008; Fox and Kemp, 2009). While interactive technology has been investigated, many recent works have focused on the design of kinetic machines and networked sensing systems for combining

sensing, computation, and physical interactions (Pan and Jeng, 2012; Rossi et al, 2012; Thün et al, 2012; Bohnenberger et al, 2012). Less effort has been made to design an eco-friendly machine that is driven by nature (e.g. air, water) and interacts with other creatures (e.g. plants, organism) as a whole ecology.

The objective of this research is to develop the concept of *eco-machine* that is able to provide sustainable solutions for moderating energy use, spatial design, and user activities. The fundamental question is: "How to achieve a green robotic eco-system that is self-sufficient and driven by natural forces?" Toward the goal of sustainability, interactions among human, machine, and environment should be concerned with the manipulation and transformation of energy, materials and information. Therefore, we propose a conceptual framework for green robotic eco-system and develop an eco-machine prototype in this paper.

2. The Eco-machine

The term "eco-machine" is commonly defined as living machine for clean, green waste-water recycling. In this paper, we define eco-machine as an ecosystem that seamlessly integrates natural resources with embedded computational devices for sustainable environments. It is argued that people need to view species, nature, and technology in a radically new way (Odum, 1971). An approach is the design of living technologies for ecological engineering (Todd and Josephson, 1996). We were inspired by the design of living technologies and attempted to develop an eco-machine using biomimic power and renewable energy self-produced by the system. To design prototypes of eco-machine, three major perspectives are considered: "Autonomous control", "Kinetic mechanism" and "Interactive materials". Combining autonomous control, kinetic mechanism and interactive materials open up new strategies for developing an eco-machine for sustainable environments.

3. Literature Review

This section provides a literature review of eco-machine with respect to autonomous control, kinetic mechanism and interactive materials for sustainable environments

3.1. AUTONOMOUS CONTROL

The concept of combining machine and living systems can be traced back since 1970s; Architect and MIT Media Lab founder Negroponte proposed "soft architecture machine" concept, and predicted that physical building will produce new form when computing technology involved (d'Estrée Sterk, 2005). However, the system integration work of former discuss are partial works of combining machinery and

building systems. There is little research to cope with architectural machine as a part of ecosystem.

Contrast to the architectural machine discussed above, we try to expand the scope of research into hybridization between machine and ecological environment. To make up a hybrid system, the operation of eco-machine should have series of environmental sensors, active actuators, and digital signal processors. These embedded computations will accommodate natural resources and adaptive functions and respond to climate change. Each autonomous entity may assemble together to become a larger organism and to share energy.

3.2. KINETIC MECHANISM

In the book "An Evolutionary Architecture" by John Frazer (1995), a set of modular intelligent blocks is developed, which outlined eight aspects of evolution system, including development through natural, self-organization, metabolism, thermodynamics, morphology, morphogenetic, symmetry breaking, and the prevalence of instability.

The book revealed the design of robotic modules for kinetic systems. In this paper, we adapt the idea of evolutionary architecture to develop kinetic robotic modules that can maximize the energy efficiency through the kinetic mechanism. The module then has functions of active control to modify the structural behaviour and generate power for maintaining the kinetic movement of the system; hence toward a new way of "zero-energy architecture".

3.3. INTERACTIVE MATERIALS

Recently, many kinds of innovative materials have been developed and integrated into the built environment. The innovative materials should be applied to a larger integral component of responsive kinetic system. The kinetic structural solutions may also include pneumatic, chemical, magnetic, natural or mechanical materials. The computation embedded into the materials and transformable objects can change the atmosphere of space through adaptable spatial configurations. Thus, the system may no longer be passive, but actively responsive to the surroundings with environmental and social adaptabilities. For instance, some newly-developed textile materials can automatically transform to adapt to the changes in temperature and lighting levels'' Such developments are confirming that the surface, structure and form are becoming more interconnected, interdependent and interactive. It requires a multi-disciplinary approach in design process. The paradigm shift from mechanical to biological in trends of architectural evolution has emerged.

4. Design Methods

In order to understand the concept of eco-machine, it is better to develop a scenario in the context of sustainable environment. The scenario is useful to demonstrate the sustainable relationships between ecology, water supply and user-lifestyles. In the scenario, eco-machine will become an important component for energy saving in future environments.

4.1. A SCENARIO

In the scenario (Figure 1), a set of kinetic physical structure is built along the seashore. The kinetic structure is actuated by hydropower and changes its form according to the sea level. We design rainwater storage and water-detecting system in order to utilize the water resource in generating the power for kinetic structures and also for flood-prevention in climate change. The water can also be collected for later use in cooling the interior or irrigating the plants on hybrid surfaces.

Figure 1. The kinetic structure is actuated by hydropower and changes its form according to the sea level.

4.2. DESIGN CONEPTS OF THE PROTOTYPE

In the above eco-machine scenario, two contradictory requirements have to be fulfilled: (1) enough renewable energy supplied for self-sufficiency; (2) adaptable kinetic structure for environmental change. However, renewable or biomass energy can produce very limited energy in each conversion and far beyond the ability to directly actuate a kinetic surface structure. The mismatch between the low energy production efficiency and high energy consumption for powering a structure is a crucial problem to be solved in this study. Therefore, we need to seek solutions by developing an embedded actuator system with minimal electronic energy consumption.

Based on the conditions above, the prototype design will follow the natural law of energy conservation and the method of potential-gravity energy storage. The prototype will gradually accumulate the potential-gravity energy, and release it at once while the amount is enough for actuating the kinetic structure. The implementation strategies include:

- **Physical kinetic mechanism design:** with emphasis on the character of "potential-gravity energy storage as the main design concept
- **Autonomous control design:** by choosing the water-detecting signal as the triggering variable in the computation algorithm.
- **Innovative material design**: by designing a layer of water-detecting modules on the façade surface as a new hybrid tectonic.

The design strategies above will bring advantages on: (1) balancing the mismatch between the low power production efficiency and high energy consumption from the kinetic structures; (2) lessening the complexity of linkage components and preserve a more usable space inside the eco-machine; (3) integrating with currently existing hydro-power network with the rainwater recycling system to set up sustainable relationship between ecology, water supply and environmental tectonics.

5. The System Implementation

The implementation will focus on demonstrating the eco-machine as a sustainable interactive component which sensitively responds to the environmental variation. The eco-machine prototype (Table 1) consists of three sub-systems: (A) Hydraulic transmission mechanism, (B) Smart surface, and (C) Embedded control systems.

Table 1. The structure profile of the Eco-machine prototype.

The Eco-machine prototype	**Structural Profile**

5.1. HYDRAULIC TRANSMISSION MECHANISM

We utilize the mechanism of potential-gravity energy accumulation. The hydraulic pressure will be accumulated to a certain extent, and then it will be released and transmitted. As depicted in Figure 2, the assembly of the hydraulic transmission mechanism includes: (A1) Liquid containers, (A2) Controllable floodgates, (A3)

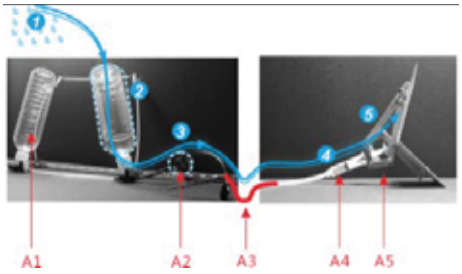


Figure 2. Hydraulic pressure transmission mechanism.

Connecting tube, (A4) Buffering component, (A5) the movable lever. The liquid container is used to accumulate the rainwater or the seawater. The controllable floodgate decides whether to release the liquid or not. The buffering component is used to prevent the over-speed releasing rate of the dynamic potential energy.

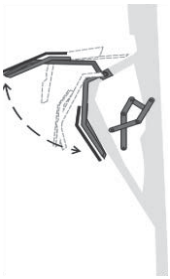
The processes of hydraulic transmission mechanics are as follows: (1) The mechanism is prepared for the collection of rain-drops or ocean water liquids; (2) The liquid collected would be kept in a container in order to accumulate enough potential-gravity energy; (3) When the controllable hydraulic floodgate is open, the liquid flows to the operational locations via the tube. (4) A syringe as a buffering mechanism is installed at the front-end to gradually release the hydraulic pressure for this kinetic structure; (5) the hydraulic pressure will push the movable lever steadily, and cause the movement of the kinetic structure. When the liquid in the container is released completely, the surface then restores to the shutting state.

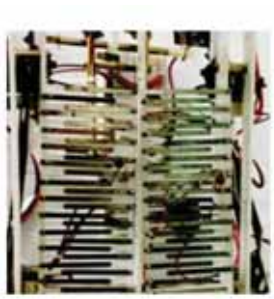
5.2. SMART SURFACE

As listed in the item (B) of Table 2, there are two main topics related to the smart surface to be discussed:

- **(B1) kinetic structures:** in the prototype implementation of this study, many operable surface modules are manufactured by CNC machines to be the kinetic components in building facade. We also used the PCB (printed circuit board) process to customize circuit board in special shapes and with electric wires and circuit elements embedded into the tectonics of the surface.
- **(B2) smart materials:** we develop a layer of water-detecting surface which is easy to be integrated with the building envelop. As depicted in Figure 3, the plural electrode array with opposite polarity plants in alternating position and maintains proper intervals between electrode arrays. Once the water simultaneously covers both of the opposite electrodes, it will arouse short-circuited occurrence and trigger the water-detecting signals for reporting the environmental event as “rainfall” or “sea-level ascending”.

Table 2. The system framework of the Eco-machine prototype.

Sub-Systems	**A- Hydraulic transmission mechanism**	**B- Smart surface**	**C- Embedded control systems**
Assembly diagram			
Elements	A1. Liquid container A2. Controllable floodgate A3. Connecting tube A4. Buffering mechanism A5. Movable lever	B1. Kinetic structure B2. Water-detecting module algorithm	C1. Micro controller C2. Autonomous computing C3. Servo motor



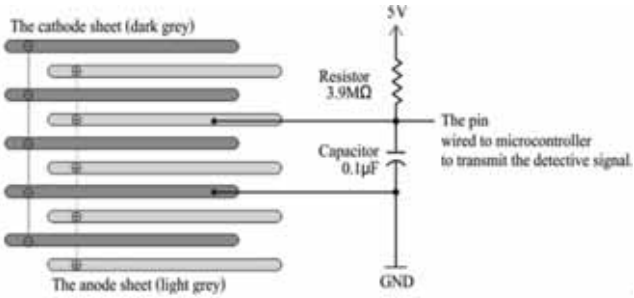


Figure 3. The photo and circuits of the water-detecting module.

5.3. EMBEDDED CONTROL SYSTEMS

As listed in Table 2, microcontroller, autonomous computing algorithm and servo motors are the three elements considered in the embedded control systems. “Arduino Mini” is the microcontroller used in this prototype. It can receive the signals from a water-detecting module and send pulse signals to a pair of servo-motors to actuate the floodgates and kinetic surface. In the microcontroller, a “triggering variable” is provided to decide whether the kinetic surface should be actuated.

The "triggering-variable" is affected by the sum up of positive and negative factors. Raindrops, manually turn-on or higher temperature are the positive factors to bring increment; while a time-based descending rate, or revolving limitation of the mechanism are the negative factors to bring decrement. While the incremental speed is greater than the attenuation speed, the kinetic surface will be actuated at the moment that the trigger threshold is reached.

The triggering-variable is controlled by an algorithm (Table 3). In the loops of computing iterations, the algorithm will repeatedly come up with new values by continuously checking the sensor's data and the time consumed. The strengths of the algorithm are as follows:

- It ignores partial and short-term effect to prevent the surface from opening up accidentally. For instance, when the surface detects very little water, it will not open.
- It ensures that the operation of the kinetic surface follows not only singular factor but also the overall situations; e.g., a user manually sends an open signal while it's rainy outside, the surface will keep closed to prevent the rainwater from flooding into the interior.

Table 3. The script of the algorithm.

Script 1: The following example used a simple algorithm to determine whether the alternation of the kinetic surface or not.

```
   int TriggeringVar, Increment, Decrement;
   int TriggerThreshold = 200 ;  // The value is specified on each situation.
   int DecayRate = 10 ;  // A time-based descending rate.
// Token of iteration start.
   LoopStart:
   Increment = 0 ;
   Decrement = 0 ;
//Conditional expressions.
   if LiquidDetect = true                    then Increment ++;
   if TemperatureOverThreshold = true        then Decrement ++;
   if ManuallyTurnOn = true                  then Decrement ++;
   if ManuallyTurnOn = false                 then Increment ++;
//Accounting triggering variable and constraining triggering variable to be greater than zero.
   TriggeringVar = TriggeringVar + Increment – Decrement – DecayRate;
   TriggeringVar = constrain (TriggeringVar, 0, 255);
//Motor Driving
   if TriggeringVar > TriggerThreshold then DrivingMotorOfFloodgate(true);
   else DrivingMotorOfFloodgate(false);
// End of this iteration and go back to starting token.
   goto LoopStart
```

5.4. PROTOTYPE DEMONSTRATION

In the demonstration, the operating sequences of the kinetic component will follow the algorithm listed in Table 3 and perform steps below:

- In the starting state, the kinetic surface is open (Table 1, right).
- Whenever the sensor detects rain-drop or water, the triggering variable starts to change incrementally, nevertheless, if no more rain-drop falls, at certain period of time, the triggering variable will start to decay by a time-based descending rate.
- For the triggering-variable, if its incremental speed is greater than its attenuation speed and reaches the threshold, the controller IC of it will send triggering signal to close the floodgate of the surface (Table 1, left).
- Until no more rain water is detected, the triggering variable will get lower than the threshold because its attenuation speed become greater than its incremental speed. In this state, the controller IC will send triggering signal to restore the floodgate to the starting state.

The components are capable of required functionality to articulate the motion of kinetic elements: (1) to store water in water collectors and pump up to get high potential energy; (2) to use the salt water to activate the motor with metal air fuel cell.

6. Discussion

In this study, we applied the accumulation-attenuation algorithm to the control mechanism of the Eco-machine prototype. The simple algorithm is very suitable for end component of the kinetic systems to improve the environmental adaptability of smart materials. Such control mechanism helps the architectural façade correctly response to the right situation in the complexity of changeable environmental parameters. The result demonstrates a surface prototype which is able to store and to release energy at right situation for operating the floodgate at the right circumstances. The prototype suggests a new direction toward an ecosystem created by a biomimic solution to the interaction between nature and built environment.

Also in this project, we have suggested sustainable strategies to the implementation of eco-machine design. Based on our observation, it is useful to combine sustainable components and embedded computation into the green robotic system. We preliminarily proved that energy consumption can be reduced in interactive systems by installing eco-machine components. Comparing to traditional interactive systems, less sensors and electronic apparatus are required in this project. The eco-machine system can be replaced by advanced tectonic and evolutionary systems to achieve sustainable performance.

7. Conclusion

In evaluating the validity of the eco-machine prototype, the implementation has proved the functionality in the following perspectives:

- **Alternative energy resources:** applying the renewable water power resources to cooling systems in order to reduce energy consumption.
- **Kinetic mechanism:** applying the accumulation of potential-gravity energy to design the kinetic mechanism.
- **Control algorithm:** using the algorithm of accumulation and attenuation to establish a self-adaptive control mechanism
- **Smart material:** developing a simple and analogical rain water sensing surface to trigger the interaction.

The experiment provides a valid proof of the "eco-machine" concept in advanced materials, alternative energy, and environmental responsiveness. However, it still needs more efforts on hybrid façade design and testing as future research direction for interactive systems. The hybrid technique applied to building façade requires totally-interwoven operation of nature materials and controlled systems.

Acknowledgements

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References

Bohnenberger, S., Khoo, C. K., Davis, D., Ramsgard Thomsen, M., Karmon, A. and Burry, M.: 2012, Sensing Material Systems – Novel Design Strategies, *International Journal of Architectural Computing*, **10**(3), 361–376.

d'Estrée Sterk, T.: 2005, Building upon Negroponte: a hybridized model of control suitable for responsive architecture, *Automation in Construction*, **14**(2), 225–232.

Frazer, J.: (1995). *An Evolutionary Architecture*, Architectural Association Publications.

Fox, M. and Kemp, M.: 2009, *Interactive Architecture*, Princeton Architectural, Princeton, NJ.

Odum, H. T.: 1971, *Environment, Power and Society*, Wiley Interscience, New York.

Oosterhuis, K. and Biloria, N.: 2008, Interactions with Proactive Architectural Spaces: the Muscle Projects, *Communications of the ACM*, **51**(6), 70–78.

Pan, C.-A. and Jeng, T.: 2012, Cellular Robotic Architecture, *International Journal of Architectural Computing*, **10**(3), 319–340.

Rossi, D., Nagy, Z. and Schlueter, A.: 2012, Adaptive Distributed Robotics for Environmental Performance, Occupant Comfort and Architectural Expression, *International Journal of Architectural Computing*, **10**(3), 341–360.

Thün, G., Velikov, K., O'Malley, M. and Sauve, L.: 2012, The Agency of Responsive Envelopes: Interaction, Politics and Interconnected Systems, *International Journal of Architectural Computing*, **10**(3), 377–400.

Todd, J. and Josephson, B.: 1996, The Design of Living Technologies for Waste Treatment, *Ecological Engineering*, **6**(1–3), 109–136.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 935–944. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

SURFACE CHANGE: INFORMATION, MATTER AND ENVIRONMENT

Surface Change project

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Abstract. Over the past decade, there has been an increasing interest in exploring the capacity of built spaces to respond dynamically and adapt to changes in the external and internal environments. Such explorations are technologically and socially motivated, in response to recent technological and cultural developments. Advances in embedded computation, material design, and kinetics on the technological side, and increasing concerns about sustainability, social and urban changes on the cultural side, provide a background for responsive/interactive architectural solutions that have started to emerge.This paper presents an ongoing design research project driven by an interest in adaptive systems in nature and a desire to explore the capacity of built spaces to respond dynamically. The paper underlines architecture's inseparable link to technology and projects a vision of architecture that, through its capacity to change and adapt, becomes an integrated, responsive, adaptive and productive participant within larger ecologies.

Keywords. Responsive architecture; dynamic environments; mechatronics; kinetic material systems; embedded systems; shape memory alloy.

1. Introduction

Thanks to current technological achievements, broadening of scientific knowledge, and greater understanding of the underlying processes that govern metabolisms of natural world, we are able to see deep connections between the made and natural worlds. With such an expansive context comes an ability to effectively and productively integrate new knowledge, information, methods and techniques back into the design and production of architecture. Confluence of various technologies and their assimilation is altering the way we perform, organize

and distribute our activities and materials. We now expect more from architecture. We expect buildings not only to house and facilitate various modes of human activity but also to adapt to, behave, respond, and accommodate the flow of energy and information.

Behaviour, adaptation and responsiveness are characteristics of live organisms; architecture on the other hand is structurally, materially and functionally constructed. But the influence of the "organic paradigm" is changing attitudes towards architectural adaptation, behaviour and performance and altering the system of reference we use for design conception (Brown, 2003). Recent thinking in science is bringing down the traditional concept of nature as a closed system governed by static rules, recognizing that everything in nature operates within dynamic and open systems (Leach, 2004). This presents a potent context for rethinking the conceptual model of architecture. Recent attitudes towards materialization and material processes (Achim Menges, Neri Oxman, Rachel Armstrong), architectural assembly and its construction (Skylar Tibbits), as well as localized control of the interior environment (Michelle Addington) remind us that processes of building and consuming architecture could be seen and practiced as life sustaining metabolic processes. The ambition to view architecture as a form of artificial life is fuelled on one hand by "material shifts occurring in the domains of energy, resources, and technology" (Brownell, 2008) and on the other by grasping a deeper connection between biological and cultural systems. In a world of depleting resources these developments might hold a key for establishing a holistic relationship between made and natural worlds; these approaches that liken architecture to a living organism propose fundamentally different attitudes towards materialization, form, performance and construction of the built environment. New content for architecture is being formulated that relies on the integration of dynamics/change into architecture – dynamics that don't address kinetic movement only but include flows of energies, material and information.

2. Change | Exchange | Flow

Thinking in terms of exchange, dynamics, energy, and flow brings forward fundamentally different attitude towards materialization, form, performance and construction of the built environment. Rayner Banham (1965) reminds us that two basic ways of controlling environment was by hiding under the tree/tent/roof (in other words, by building a shelter) or by mediating local environment by campfire. He points out that "a campfire has many unique qualities which architecture cannot hope to equal, above all, its freedom and variability." This observation hints at an unexplored potential to re-conceptualize the environmental control. By shifting a discourse from form to system Banham locates architecture's agility not

in its formal and structural expression but in the realm of building systems/technology (Kulper, 2012) emphasizing that architecture's relationship to technology must intensify in order for architecture to stay relevant. He alludes to technology's capacity to deliver a radically different way of living as well as frame future architectural discourse and experimentation. This predicates the most recent attitudes about environmental control that mediate conditions locally not globally and in relation to a body not space – relying on a material that does not need thermal mass but regulates the heat exchange within a thin zone of a few millimetres (Addington, 2008).

Similarly to Banham's focus on building systems, Gordon Pask (1969) emphasizes architecture's "operational" capacity (and its "intimate relationship" to cybernetics) by pointing out that "architects are first and foremost system designers". The focus on architectural systems from the organizational and operational aspects extends Bahnam's idea of the flow of energy to include the flow of information. Several projects/ideas that developed in the late 60's and early 70's such as Cedric Price's Fun Palace, Negroponte's Soft Architecture Machines, Eastman's concept of "adaptive-conditional architecture" began to explore "intelligence" and programmability of architecture's processes and spaces in order to facilitate the flow of information between spaces and users.

Current technological achievements as well as expansion of our understanding of the underlying processes in nature brought about a new generation of projects exploring deep connections between made and natural worlds. In 2003 Kas Oosterhuis and his Hyperbody research group designed and constructed the Muscle, a working prototype of a "programmable building that can reconfigure itself". The Muscle is the first in a series of Pro-active Architecture (ProA) projects that study design of responsive buildings that exhibit real-time behaviours and adjust shape in response to changing environmental circumstances. The Muscle is a pressurized soft volume, wrapped in a mesh of tensile Festo "muscles," which can change their own length and, thus, the overall shape of the prototype. The public connects to the prototype by sensors and quickly learns how the Muscle reacts to their actions; the Muscle, however, is programmed making the outcomes of interactions unpredictable. The ProA projects test capacity of buildings to respond in real time and explore a range of enclosures and programmatic situations. They demonstrate that responsive and kinetic architectural systems are not so techno-utopian and that spaces that move, transmit information, or adjust to a feedback could perhaps become a reality of our inhabitation in the future. They offer a promise of a "total" environment that could be inhabited, touched, moved into action and above all responsive. Surfaces/spaces like these could be at the same time architectural spaces and through their agility have a capacity to adjust to a productive role of harvesting or distributing energy or information.

3. Surface Change Project

Buildings that change in real time can be many things: they can change their functionality, perform several functions at the same time, change form and physical location, harvest and distribute energy. The Surface Change project is an ongoing design research project focused on the integration of information, matter and environment. The ambition is to develop technological/tectonic solutions that can provide buildings with a (biologically inspired) capacity to transform and adapt. A fully developed project will result in a system by which responsive dynamic structure/skin will be capable of altering its shape or its regions based on environmental conditions and the nature of use. At the same time the system would address questions of energy capture and energy harvesting. The goal is to develop technologies and designs capable of transforming static building components into active responsive surfaces that produce added functionalities in architectural and urban environments and enable architecture to become a productive participant within larger ecologies.

The ambition of this phase of the project is to explore a material system that would make movement and adaptation possible without employing mechanical components. The SKiN project (first phase of the Surface Change project), presented here, consists of small scale prototypes of an adaptive kinetic surface capable of spatial modulation and response to environmental stimuli by using shape memory alloy (SMA) as an actuator. The presented work focuses on the layering of material system and studies of its movement.

3.1. MATTER: MATERIAL SYSTEM ACTUATION AND LAYERING

Material systems in nature don't distinguish between material and structure. In order to achieve adaptation and responsiveness they involve movement (Jeronimidis, 2004). This movement is both local and global resulting in a complex pattern produced by accumulation of the local movement effects. Furthermore, material systems in nature don't distinguish between structural and functional material instead, variation of material properties determines and fosters certain behaviours that result in change of form, shape or location. Information travels through integrated material layers and functional needs inform material and structural distribution. The SKiN project was inspired by these characteristics of material systems in nature. We were interested in producing and understanding the "mechanism" of surface movements that would capitalize on local movements to generate a global pattern. At the same time we wanted to relate these patterns of movement to structural and functional properties of the surface. Experimenting with flows of movement, energy and information was intended to bring us closer to a material system that would reveal qualities of "freedom and variability" possessed by natural material systems, and enable us to harvest the power of phenomena in a more effective way.

We began the movement studies by focusing on actuation of the surface and designing a soft network with movable joints. This soft kinetic network (SKiN) consisted of "V" shaped memory alloy joints embedded in the silicon tubing. The network joints were "programmed" to open and close and by doing so to generate movement of the entire network. This experiment examined SMA wire joint capacity to act as a point source of actuation of the surface. To better understand the gradient of movement the grid was restricted by anchoring joint points to a flat surface in a variety of configurations. Depending on the configuration, the behaviour ranged from expanding grid cells to vertical movements of the grid's regions. The vertical movement was surprisingly agile and pronounced. It reached its maximum when end points of the grid were anchored (Figure 1). These studies suggested potential structural capacity of the surface with pattern of anchoring directly related to the three dimensional spatial delineation.

The second experiment examined SMA wire capacity to act as a linear source of actuation. Instead of "V" joints we used 'long' (45cm) lengths of SMA wire (baked into large amplitude (15cm) waves) treaded through the silicone tubing grid. While technically challenging, this new method of using the wire enabled easier control and more dramatic movement results. The silicone tubing grid was then integrated into a silicone surface in order to create a dynamic material system. The fusion of the grid and silicone cells created a structural yet flexible surface that achieved a certain level of material equilibrium: the SMA wire pulled the surface into a particular shape while silicone layer contained in the cells of the grid pulled the material system back to its original shape. In this experiment the accumulation of the local movements resulted in a complex global movement where each shift of a cell depended on the movement of adjacent cells or regions. To better understand and analyze the deformations we filmed the motion and used motion tracking to map the movements (Figure 2).

Both, point and linear actuation provide a good strategy to capitalize on aggregation of local movements to produce global dynamic surface effect. Point

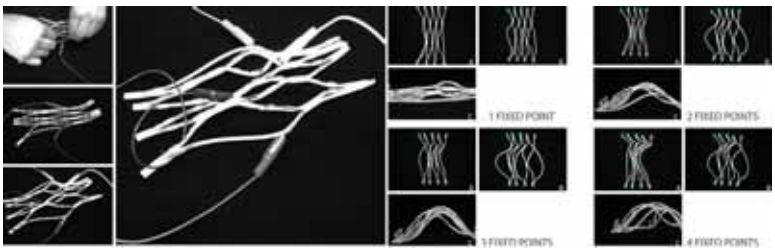

Figure 1. Point actuation using "V" joints and fixed point test showing the grid deformation.

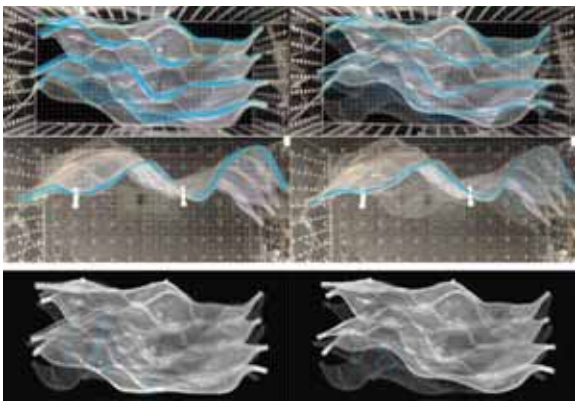

Figure 2. Using motion tracking to map the movement of the diagrid points.

actuation facilitated greater variety of movement. Within this system continually reversed joints could produce twisting movement. Linear actuation produced more dramatic movement and reduced the number of connections between the electrical wire and the SMA. Combination of these two strategies could lay out number of patterns that produce dynamic surface choreographies. Tying these choreographies to functional requirements would produce surfaces or spaces with movements tightly related to their use.

In the course of these experiments we became interested in the material variability of the surface. The variability in the material system would enable different behaviour within surface regions such as variation in the speed and degree of movement and variation in surface transparency. These experiments in material variability resulted in our current preoccupation with making pillows that would hold heat storage material and facilitate heat transfer through the surface. We are currently working on this aspect of the project (Figure 3).

The pillows have a two-fold role: to store and transmit the heat, and to participate in the movement/deformation of the surface by changing the volume of the diagrid cell. This builds upon Banham emphasizes on “freedom and variability” of a campfire. But instead of a localized heat source specific to its placement within the space the proposed pillows would work as a distributed system that can be activated locally and only where needed. Viewed in this context of flow and exchange a “campfire” can become an intelligent surface capable to instil the “freedom and variability” into architectural form/space/surface by overlapping the phenomena and flow with materiality of architectural environment. This approach would offer an opportunity to suspend a challenge of finding a non-permeable and clearly defined boundary between inside and outside in exchange for a surface that

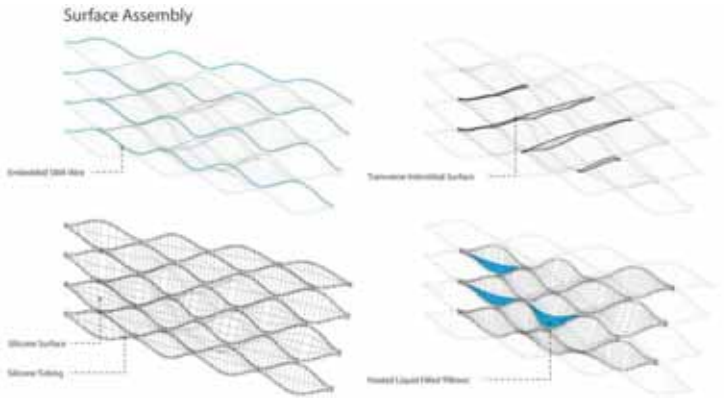

Figure 3. Assembly of the surface with "heat storage pillows".

fosters constant flow of information, matter and energy and through its own dynamics delineates and forms agile spaces.

The broader goal of the project is to design elements, structure, surface and performance of the kinetic material system as integrated layers that make up a "tissue" capable of accommodating movement related to human occupation, energy harvesting and different external/environmental influences, where two way relationships exists not only with users but with the environment as well.

3.2. INFORMATION, MATTER AND ENVIRONMENT

Our goal to design an integrated, "tissue" like material system that has a two way relationship with users and the environment required integration of sensory input and other kinds of external and internal data. We used Arduino microcontroller platform to explore these possibilities. Arduino was used to control the application of power to the SMA string as well as to incorporate sensory input and other external information. Firefly plug-in bridged the gap between Grasshopper and Arduino and was used among other things to integrate local historical weather data as an input that would allow for our surface to respond to dynamic patterns. Movement of the surface became an abstract representation of changes in temperature. The prototype was also equipped with photo sensors that would react to the change in light level. These sensors were only a place holder for a more sophisticated setup that would include temperature and humidity sensors capable of collecting a real time weather data and influencing the movement of the surface in real time.

Bringing in historical weather data enabled us to actuate our system by bringing in external information in order to explore the connection between spatial

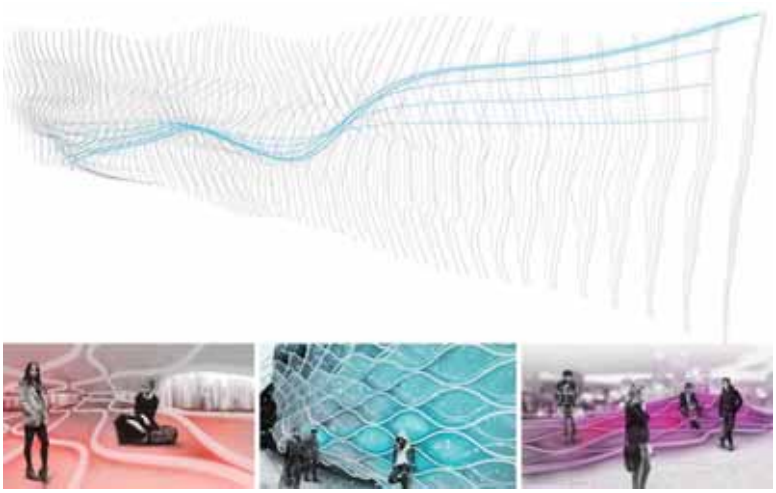

Figure 4. Possible uses based on functional requirements and information input.

modulation and environmental input. We achieved our goal of implementing dynamic data patterns and yielding dynamic geometric responses.

Tying the patterns of movement produced by environmental input with functional requirements of spaces would enable surfaces or spaces to adapt and respond to external environmental conditions as well as to functional requirements of use (Figure 4).

Next iteration of this exploration will address direct relationship between the environmental input and specific spatial configuration. In other words, the particular input should be able to produce specific formation of the surface that is related to the functional requirements.

4. Conclusion

In summary, the proposed surface is organized around the network of embedded "muscle" wires that change shape under electric current. The network of wires provides for a range of motions and facilitates surface transformations through soft and muscle-like movement. The material system developed around the wire network is variable and changes its thickness, stiffness, or permeability within its continuous composite structure. The variability in the material system enables it to (a) behave differently within surface regions; (b) vary the speed and degree of movement; (c) vary surface transparency; and (d) provide other levels of performance such as capture of heat produced by the muscle wire and distribution of

heat within the surface regions. The main idea is that variability of the material system and its capacity to adapt can bring us closer to the seamless material integration and greater environmental responsiveness found in biological organisms.

In the next phase of the project the focus will be placed on scaling up of the material system, further pursuit of seamless integration of the SMA (and other smart materials) into a tectonic material system and development of a more robust micro-controlling and sensing system.

Working with smart materials presents a significant challenge especially on the scale of an architectural element or surface. Traditionally architectural components are assembled using several different material layers and every one of them has its specific role and material properties. Smart materials, on the other hand, are not artifacts; they are technologies of motion, energy, and exchange. Their integration in architecture offers an opportunity to re-calibrate materialization of architectural components and surfaces. The challenge is to build architectural assemblies that integrate and fully utilize the capacities and properties of smart materials. The functional qualities of smart materials/technologies that transfer energy and/or information would have to achieve a full overlap and integration with structural/tectonic functions of a material system necessary for architectural applications. In this way the change of scale, currently one of the greatest challenges in the projects of this kind, would be more effectively addressed. Experimenting with fuller integration of SMA was one of the aims of our project. The next phase of the project will take this further by changing the scale of the system and attempting to capitalize on discrete and local movements to produce larger global effect on the surface.

This project is situated between several disciplinary territories. By exploring theories, techniques and tools of architecture, engineering, material science and cybernetics the goal is to develop technologies and designs that are capable of transforming static building components into active responsive surfaces that produce added functionalities in architectural and urban environments.

If we were to accept change as a fundamental contextual condition, architecture could then begin to truly mediate between the built environment, the people who occupy it and the larger context. As Ed van Hinte et al. (2003) note, “instead of being merely the producer of a unique three-dimensional product, architects should see themselves as programmers of a process of spatial change.” The principal task for architects is to create “a field of change and modification” that would generate possibilities instead of fixed conditions.

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References

Addington, M.: 2008, "The Architecture of the Unfamiliar". Available from: <http://fora.tv/2008/04/17/Michelle_Addington_The_Architecture_of_the_Unfamiliar> (accessed 10 April 2012).

Banham, R.: 1965, A Home is not a House, *Art in America*, **2**, 75.

Brown, G.: 2003, Freedom and Transience of Space (Techno-nomads and trans-formers), *in* R. Kronenburg (ed.), *Transportable Environments 2*, Spon, London, 3–13.

Brownell, B.: 2008, Material Ecologies in Architecture, *in* L. Tilder and B. Blostein (eds.), *Design Ecologies: Essays on the Nature of Design*, Princeton Architectural, New York, 221–237.

Jeronimidis, G.: 2004, Biodynamincs, *in* M. Hensel, A. Menges and M. Weinstock (eds.), *Emergence: Morphogenetic Design Strategies*, Wiley Academy, Chichester, 92–95.

Kulper, A.: 2011, Ecology without the Oikos: Banham, Dallegret and the Morphological Context of Environmental Architecture, *field:*, **4**(1), 67.

Leach, N.: 2004, Swarm Tectonics, *in* N. Leach, D. Turnbull and C. Williams (eds.), *Digital Tectonics, Willey Academy*, Chichester, 70–78.

Pask, G.: 1969, The architectural relevance of cybernetics, *Architectural Design*, **39**, 494–496.

van Hinte, E., Neelen, M., Vink J. and Vollaard, P.: 2003, *Smart Architecture*, 010 Publishers, Amsterdam.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 945–954. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

RESPONSIVE BUILDING ENVELOPE AS A MATERIAL SYSTEM OF AUTONOMOUS AGENTS

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Abstract. The paper represents the concept of an abstract model of the responsive building envelope (RBE), founded on pre-programmed material's behaviour. The assumed model of the responsive building envelope is based on the idea of material autonomous agents that control default parameters of building's energies like ventilation, humidity, light volume, radiation, temperature, etc., by materials' geometry deformation. The agent is a material system, built with the electroactive polymers (EAPs) actuators which react to the environment's fluctuations continuously and independently from other agents. The model of a responsive envelope is a cluster of self-reliant units which control the primary characteristic of the building environment in an analogous way to the homeostasis system of a living organism. By decentralization the system becomes more stable and reliable. The CFD simulation was created from the schematic model of the RBE's performance to test the presented design concepts.

Keywords. Responsive system; autonomous agent; electroactive polymers (EAPs); homeostatic cycle; CFD simulation.

1. Introduction: Architecture as a Responsive System

Responsive architecture can be characterised as: *a system which reacts on given stimulus in predefined way*. The system's state can depend on the interactions with the non-system events, thus the system's reactions can be reliant on the outer actions and the current characteristics of the system.

In architectural context the term *responsiveness* can be divided in several types which can be collected in general into two main groups:

- *presentational/form responsiveness* – the building components react on the user or environment behaviour, not affecting the general characteristic of the building system (i.e. interactive facades, digital screens, kinetic elements, etc.);
- *functional responsiveness* – the building's system characteristics change under external stimulus (i.e. automatic shading systems – internal temperature increase

> under the solarisation – the system responds by changing his geometry to decrease a light volume and therefore a temperature, etc.).

Groups mentioned above can be divided into two additional subgroups (Addington and Schodek, 2005):

- *micro – level of responsiveness:* mechanism of adaptation changes system's components material properties – i.e. thermophysical or optical material properties, energy state change – i.e. electricity to light due photovoltaic cells, or electricity to thermal radiation;
- *macro – level of responsiveness:* mechanism of adaptation changes geometry of building's envelope by moving its components to demanded configuration (by folding, sliding, rotating, opening, inflating, etc.).

This article will concentrate on the second group of the responsive building envelopes only.

The *functional responsiveness* in contemporary architecture can be defined as (Ferguson et al, 2007):

> system's ability to adapt itself to deliver intended functionality under varying conditions through the design variables changing their physical values.

Cited definition can be rearranged and simplified for a building system to: *a system that controls building's energy balance by its elements manipulations*. The design process of these systems focused on the *responsive building envelopes* (RBEs) development, where external environmental conditions (like ventilation, humidity, light volume, radiation, temperature) influence the interior parameters of the building (i.e. thermal and light comfort). The most common solutions are based on several specialized subsystems (like structural elements, sensors, mechanical actuators, membranes, control devices, etc.) that are responsible for changing the envelope's geometry according to stimulus and programmed performance. The application of these systems concern on the solar shading systems and the bio – inspired building skins (manipulation of the 'pore' element to control the air flow between interior and exterior) (Figure 1).

The implementation of the responsive envelopes in contemporary realisations is very unique and rare. Responsive shading systems were applied in: i.e. Institute du Monde Arab in Paris by Jean Nouvel, or more current Al Bahar Towers in Abu Dhabi by Aedas (more examples can be found in Anshuman, 2005; Loonen, 2010). The responsive 'pore' system hasn't been implemented in full scale project yet, and it is still in conception (i.e. Dutt and Subhajit, 2012; Doumpioti, 2011) or prototype phase (i.e. 'Bloom' installation by Doris Kim Sung, 2012).

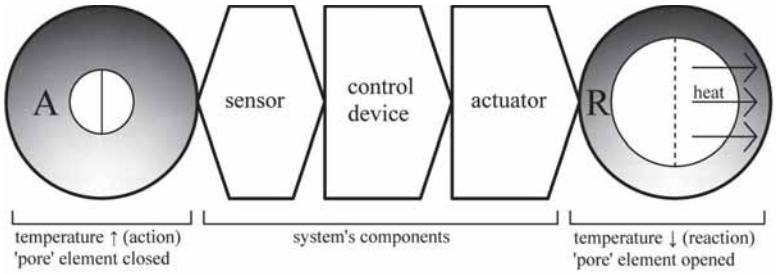

Figure 1. Scheme of the responsive system components (A – external action, R – response on external action).

2. Responsive Distributed System and Material Auto-responsiveness

Current responsive building envelopes (RBEs) are based on hierarchical relations between system's elements with a central control device which maintains system's behaviour. Although the overall performance can be effective, the stability on the unpredicted perturbations can be low, reliant on system's central scheme (i.e. local failure of the actuator mechanism, or sensor will effects the whole system). The decentralisation of the scheme can increase the system's local and entire performance and makes the system more reliable to external disturbances. The result of distributed system scheme is the subsystems' elements multiplication (i.e. sensor, mechanism, control devices, etc.) and therefore growth of energy consumption.

The system simplification with the energy reduced consumption can be achieved by the minimisation of the subsystems and their elements. The design scheme is based on the *material auto-responsiveness* paradigm – the material is being programmed to react on the stimulus in defined way. The behaviour is independent from other system's components and based only on material embedded properties. The material reaction for the application of external impulse is a shape deformation that can be converted into a functional responsive mechanism.

The implementation of the mechanism can be achieved by using the components based on the shape memory polymers (SMPs) – particularly the electroactive polymers (EAPs).

3. Electroactive Polymers (EAPs) Materials

From the various types of the active materials (i.e. shape memory alloys, bimetals, piezoelectric, ceramics, polymers, etc.) EAPs dielectric elastomers (DE) have the most applicable performance parameters (strain, reaction speed, efficiency, low energy of actuation, operating temperature range, etc.) for application into the

RBEs' components (Bar – Cohen, 2004; Lochmatter, 2007). The principle characteristics of the EAPs DE to shape changing under the electric stimulation can be used to react on a relatively small and rapid environmental conditions change (i.e. temperature, humidity, light volume, etc.) with the pre-programmed geometry change (up to maximum strain), which is difficult to achieve using on the previously mentioned active materials due to their properties limitations (Madden, 2005).

The material properties of the EAPs DE allow to design components which will deform in predicted way. The material displacement can be used into development a *soft mechanical* actuators for the responsive building envelopes (RBEs). The calibration of the material performance can adjust the previously mentioned paradigm of *the material auto-responsiveness* in which the material system behaves in the way of a well-tuned device. For the purpose of this article a simplified model of the EAPs DE component behaviour was developed. The EAPs DE elements are represented by element's geometry deformation before (G_0) and after (G_E) application of an external stimulus.

4. Homeostatic System: Material Homeostatic Cycle

Definition of the term *homeostasis* can be described as (Moioli, 2008):

> a successful adaptation of the system to dynamic environments.

The general definition of *homeostasis* can be formulated as the ability of the system to maintain its parameters in a defined range to keep the system in a state of equilibrium. The grounded idea of homeostatic system (a system with ability to conduct homeostasis) can be related to the term of the *functional responsiveness* and further with the *material auto-responsiveness*. Based on the SMPs (EAPs') material properties it is possible to design an element (sub – system for a responsive envelope) that controls system's parameters in balance directly by the *material homeostatic cycle*.

The *material homeostatic cycle* is a continuous process in which pre-programmed material performance controls attributed system's domain parameters: if the system stability is interrupted by external change (i.e. defined range of the internal temperature is crossed) the system reaction is geometrical deformation of the material/component element *(auto-responsiveness)* in the way that allows to return to system's equilibrium. The reaction occurs without any external control devices and is eternally based on a material/component embedded properties (Figure 2).

The material homeostatic cycle (homeostatic cycle's steps: $1\rightarrow2\rightarrow3\rightarrow4\rightarrow[1]_{virtual}$).can be used as the basic principle for the responsive envelope development (RBE). Furthermore, buildings (or any architectural object with the embedded maintenance of physical parameters) can be seen through the paradigm of buildings as: a *continuous homeostatic process*.

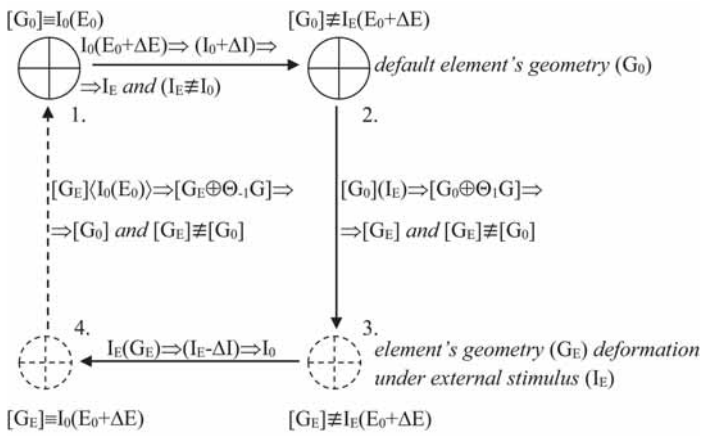

Figure 2. Schematic of the auto-responsive material agent's behaviour in a homeostatic cycle: G0 – default EAPs geometry of element, GE – final geometry of element under external stimulus, $\Theta_1 G/\Theta_{-1} G$ – theta change element's geometry, I0 – default internal parameters, IE – final internal parameters, ΔI –delta change of internal parameters, E0 – default external parameters, ΔE –delta change of external parameters, ⊕ - operator of geometry change, +/- - operator of external/internal parameters change, ≡/≠- relational parameters between environmental conditions and elements' geometry.

5. Autonomous Material Agents System

The primary scheme for responsive skin performance is a collective of pre -programmed material agents that control set-up of building environmental characteristics. Material agent definitions came from the computer science background where term *agent* is described as (Stamatopoulou et al, 2005):

> an encapsulated computing system that is situated in some environment and is capable of flexible, *autonomous* actions in order to meet its design objectives.

In more general definitions *agent* can be defined as *autonomous* object (Weiss, 2000):

> that takes sensory input from the environment and produces an output actions that affect it.

From the various types of an agent samples (i.e. intelligent, smart, learning, etc.) the most suitable model for the application in the material systems is a *reactive agent*. The reactive agent's behaviour is based only on its present situations with a simple rule scheme (adopted from Weiss, 2000):

$$\text{Action: Perception} \rightarrow \langle \text{Reaction (Action)} \rangle \qquad (1)$$

Agent's behaviour is without any reference to the history of the previous actions and its decisions are purely autonomic (no communication amid other agents).

For the purpose of the responsive envelope development an agent was adapted as a material system that inherits a similar *reactive agent*'s model of performance with a rule that allows to conduct the *continuous homeostatic process*. The material agent system is: *an autonomous unit that responses only on stimulus from surroundings and controls only its parameters*. The autonomous material agent can be a single element, or a cluster of elements (that retains listed before properties). Their common feature is the possibility of an asynchronous behaviour (cluster's cells behave in synchronous way but in relation to different clusters on the same domain their states can be various) which is caused by different stimulus from the environment (i.e. various temperature range for the same domain) (Figure 3).

Autonomous material agents due to their independent performance and control (every agent is controlled by itself) provides a steady and reliable responsive system – i.e. if one of the system's unit has a defect its responsibilities are intercepted by the others. Although overall system's performance is lower – the principle of homeostasis stabilizes its parameters on the defined levels.

The bottom – up approach that summarizes the scheme of *the functional responsiveness* of the building systems can be found below.

> [material properties] → [material auto – responsiveness] → [material homeostasis cycle] → [material agent] → [responsive structure] → [functional responsiveness]

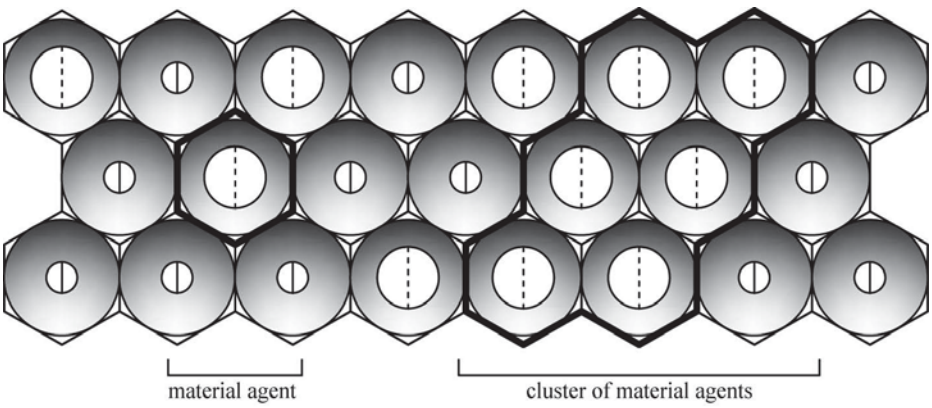

Figure 3. Scheme of material agent unit and cluster of material agents units in RBE's domain.

6. Application of Autonomous Material Agents System into Responsive Building Envelope

The studies of the plants stomata mechanism helped in developing abstract model of the responsive building envelope. Stomata is a complex system of a pores that regulate gaseous exchange process in plants. Stomata performance depends on regulation of the size and the opening of the pore to control the amount of gas exchange between internal air space and external atmosphere. The responsive behaviour of the stomata structure depends on inner chemical equilibrium which is a main factor of the pores shape change (Kramer and Boyer, 1995) (Figure 4).

The abstract scheme of responsive building envelope was developed as an implementation of stomata self-regulation mechanism. The model presents simple fragment of the responsive envelope with the regular grid of pores. The pores scheme is an application of *autonomous material agent system*: in designed arrangement every single pore is a material agent with embedded responsiveness scenario. The applied behaviour can be expressed as a simple conditional statement (2):

$$\text{Pore: } \textit{If}\,(ti > tm) \rightarrow \text{Open(Pore)}\ \textit{Else}\ \text{Close(Pore)} \tag{2}$$

ti- internal temperature in pore's surroundings; *tm*- maximum default temperature in pore's surroundings in relation with external environment.

The responsive scheme model is designed to stabilize the internal temperature in the default pore's surroundings: if the temperature crosses default value – the

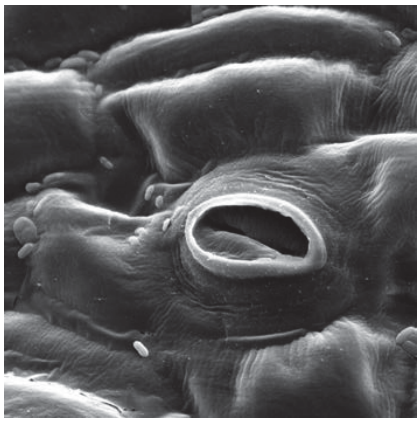

Figure 4. Tomato leaf stomata
(source: http://remf.dartmouth.edu/images/botanicalLeafSEM/source/16.html).

pore will open and allow heat to transfer from the environment with the higher temperature to the lower. The *autonomous material agent system* grounded on the EAPs and their composites is able to maintain internal conditions on default level with this reduced rule-based procedures. At this stage of the research the behavioural model is simplified to single binary logic and the most common situation (*indoor temperature* > *external temperature* or *indoor temperature* < *external temperature*). The more complex situations will be considered in further research.

7. CFD Simulation of Schematic Responsive Building Envelope Performance

For this research purpose, the CFD (*computational fluid dynamics*) simulation of responsive building envelope was made. The schematic of the interior model was assumed with the responsive building envelope containing 'stomata' elements. The assumed interior's dimensions were: 3x6m, 'pore' element's width – open: 0.10m (total cluster's opening: 30% of the façade), - closed: 0.00m. The 'pore' element

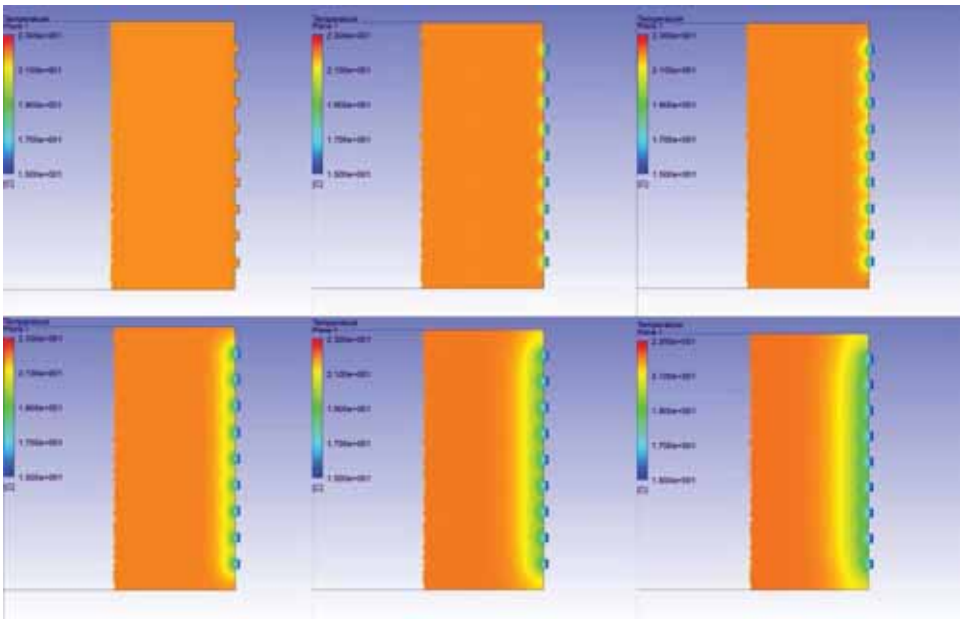

Figure 5. CFD simulation of responsive building envelope's 'pores' opening performance (a fragment of room with the schematic RBE). The pores open when the temperature in the pointed measurement is (t_i>22°C) and close when ($t_i \leq 18$°C).

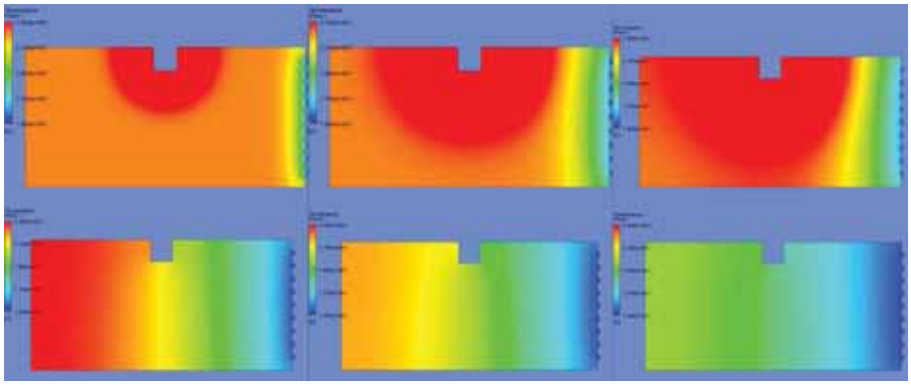

Figure 6. The simulated RBE's behaviour was able to reduce the interior temperature (t_i) to the default level. With the proper optimization of the RBE's control parameters in relation to the heat source is possible to receive a closed – loop temperature control.

performance was an *autonomous agent* with the embedded control scenario (2). The element controls the heat flow between mediums with *open* or *close* state. The temperature measurement point was done for 'stomata' cluster: 5,0m from the cluster and 1,5m form the floor in one local point. The 'pore's' boundary temperature was set: for $t_m = 22°C$; for $t_{exterior} = 15°C$. The interior air was heated by a circulated heat stream (heat source with power $30W/m^2$ localized in the middle of the ceiling) with the initial interior's temperature $t_{interor_initial} = 18°C$ on the *closed* 'pore's' state. The heat source is set – up to *turn on* when a temperature in the default measurement point is ($ti < 18°C$) and *turn off* when ($ti \geq 23°C$). For the simplification of the simulation process the wall's thermal conductivity was set to 0 [W/(m•K)].

The simulation showed that the 'pore' elements performed synchronously (as a cluster), according to their default pointed temperature measurement: if the temperature (*ti*) was higher than the boundary temperature (*tm*) the element changed its geometry (*open* state) to enable a heat flow (Figure 5).

The study of the CFD simulation showed that the performance of the RBE's model is able to reduce an interior temperature (t_i) to the initial level ($t_{interor_initial} = 18°C$) which implicates the ability to control the system's temperature state in the *homeostatic cycle* (Figure 6).

8. Conclusion and Further Work

The RBE's schematic model founded on the *material auto-responsiveness* presented in this paper reveals potential for further research for the stage of physical implementation. The studies showed that the multi-layered system behaviour of

RBE's model can be simplified to set of subsystems that control the ambient interior climate condition autonomously (*material agent or cluster*). Implemented in RBE's model distributed system of building's energies control contributes stable and efficient structure's performance. The next step for the RBE's model development should be intensive studies on CFD simulation that analyses various scenarios of the building energies environmental exchange (heat, humidity, air – flow, etc.) under diverse conditions. Simultaneously the research on physical models should be conducted to compare the results with the computational models and optimize them according to their efficiency and constancy of operation.

References

Addington, M. and Schodek, D.: 2005, *Smart materials and new technologies: for the architecture and design professions*, Elsevier, Amsterdam.

Anshuman S.: 2005, Responsiveness and Social Expression; Seeking Human Embodiment in Intelligent Façades, *Smart Architecture: Integration of Digital and Building Technologies*, Association for Computer Aided Design in Architecture (ACADIA), Savannah, GA, 13–16.

Bar-Cohen, Y.: 2004, *Electroactive polymer (EAP) actuators as artificial muscles: reality, potential, and challenges*, *SPIE Press Monograph*, vol. 136, Society of Photo Optical.

Doumpioti, C.: 2011, Responsive and Autonomous Material Interfaces, *ACADIA 11: Integration through Computation*, Association for Computer Aided Design in Architecture (ACADIA), Banff, Alberta, 318–325.

Dutt, F. and Subhajit, D.: 2012, Responsive architectural surface design from nonlinear systems biology: Responsive architectural design by computational methods, *Proceedings of the 17th International Conference on Computer-Aided Architectural Design Research in Asia CAADRIA 2012*, Association for Research in Computer-Aided Architectural Research in Asia (CAADRIA), Chennai, 465–474.

Ferguson, S., Siddiqi, A., Kemper, L. and de Weck, O.: 2007, Flexible and reconfigurable systems: Nomenclature and review, *Proceedings of the ASME 2007 Design Engineering Conference*, Las Vegas,Nevada.

Kim Sung, D.: 2012, "Thermo – bimetal research". Available from: Open Source Repository <http://tbmresearch.blogspot.com/> (accessed 14 November 2012).

Kramer, P. J., and Boyer, J. S.: 1995, *Water relations of plants and soils*, Academic Press, New York.

Madden, J. D.: 2005, "Actuator summary". Available from: Open Source Repository <http://www.actuatorweb.org/index.php?page=summary/> (accessed 14 November 2012).

Lochmatter, P.: 2007, Development of a shell-like electroactive polymer (EAP) actuator, Verlag Dr. Hut., Munchen.

Loonen, R. C. G. M.: 2010, Climate adaptive building shells–What can we simulate, MSc thesis, Eindhoven University of Technology.

Moioli, R., Vargas, P., Von Zuben, F. and Husbands, P.: 2008, Evolving an artificial homeostatic system. *Advances in Artificial Intelligence-SBIA 2008*, *Lecture Notes in Computer Science*, Springer, Berlin, 278–288.

Stamatopoulou, I., Gheorghe, M. and Kefalas, P.: 2005, Modelling dynamic organization of biology-inspired multi-agent systems with communicating x-machines and population p systems, *Proceedings of the 5th international conference on Membrane Computing*, Springer, Berlin, 389–403.

Weiss, G. (ed.).: 2000, *Multiagent systems: a modern approach to distributed artificial intelligence*, MIT press, Cambridge, MA.

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 955–964. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

TRAN[S]QUILLITY: THE DYNAMICALLY MEDIATED FAÇADE

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Abstract. Media façades grant infinitely many faces to a building and can change the architectural meaning of what a façade is. They can also help to transform the face of the building into an over-size communication device for public (Borras, 2010). Contemporary media façades mostly rely on the content of their screens, and only a small number of them physicality of the screen itself. Precedent building façades that incorporate moving components are unable to function as displays. In this paper we present a media façade design, titled "Tran[s]quillity", in which we fuse reconfigurable building components with display technologies to achieve a unique design. As well as fulfilling the function of a regular media wall -as a crisp screen- we imagine Tran[s]quillity as a transformable kinetic sculpture that can act as a screen of physical depth to introduce greater functionality and interactivity.

Keywords. Media; façade; kinetic; LED; image processing; digital; design; architecture.

1. Introduction

This paper introduces a commissioned experimental media façade project, called Tran[s]quillity. The project aims to grant maximal visual transformability to Pandora, the building on which it will be functioning. Pandora is a proposed building to be located on the gateway to the City of Venice, and thus it requires in depth architectural investigations. We discuss the architectural aspects in relation to building's location and function. Tran[s]quillity consists of a physically-reconfigurable array of display screens, so it also requires detailed technical investigations. For development of this unprecedented façade configuration, we utilize computational design techniques and incorporate mechanical parts. We benefit from CAD simulations and animations. We build a scale prototype to test feasibility of our design. The documentation about our fully-functioning scale prototype reveals both the potentials and limitations of our proposal.

2. Project Background

Tran[s]quillity was developed mostly during our course work at the Media LAB at Massachusetts Institute of Technology in the fall 2011 semester. An innovation company, VEGA (VEnice GAteway for Science and Technology), located in the City of Venice, was our project partner. They commissioned a series of innovative projects to be implemented for their proposed office building, Pandora. Projects varied in scale, physicality and target user. A media wall was in the list of requests; however, it was not imagined to be something beyond a conventional flat media façades made of LED lights. From the very beginning of the project, we sought a media wall that would not merely act as a surface to adorn the façade. We conceptualized the media wall as a transformable object that would become a space defining element on the façade (Haeusler, 2009). We started with a concept we called "greater than 2D" [>2D] and explored ways to generate a physical depth via use of simple components and simple geometric transformations (Figure 1). Our aim was to *stimulate* the north-facing blind façade of Pandora. This façade measures approximately 16 meters in width and is 39 meters tall. The media façade is planned to cover the top portion of the wall, leaving 12 meters of clearance from the ground.

Figure 1. Collage of the concept [>2D].

3. Precedents: Contemporary Designs of Interest

We analyse a wide spectrum of media façades and compare and contrast their visual features and technical specifications. Here we discuss the media façades that inspire us as well as the ones that help us elaborate on limitations.

To start with, the media screens that adorn the façades of the buildings in Time Square in New York City represent cutting-edge examples of bright, crisp and flat media walls. Although some of these screens are curved and they envelop the

corners of buildings, they are still flat in nature; they can only display 2D visual content without any hints of physical depth.

At the other end of the topological spectrum, we examine Heatherwick Studio's UK Pavilion, which was constructed for the Shanghai World Expo in 2010. Sixty thousand 7.5m long transparent fibre-optic rods protrude from the pavilion façade to create a gentle, soft fur around the building. UK Pavilion demonstrates how physical depth can create striking visual effects that contribute to the architectural manifestation of a building. With its subtle colour scheme and gentle patterns that emerge with forces of nature (such as wind or sunlight), the UK pavilion features an organic skin.

DECOI's renowned HypoSurface renders the most compelling example amongst all contemporary full-scale dynamic wall designs. Although the surface performs beyond any of its predecessors, the cost, maintenance and application scale reduces its applicability as a façade installation. Staab Architect's Flare Façade, which is a larger scale application, suffers from complexity and cost of its individual components.

Simon Heidjens' "Shade", which is an installation that was exhibited as a part of the Hyperlinks Exhibition at the Chicago Art Institute (Heidjens, 2010), inspires us with its potential to capture the forces of nature and to use them in generating ever-changing real-time light effects for interior spaces. It is a very lightweight installation that benefits from deviating material properties of special films on glazing. It cannot be used for displaying any sort of digital content.

Although not a façade installation, the interior hybrid-material installation of the Greenhouse Nightclub in NYC by Bluearch inspires us with its success in merging materials.

We incorporate our inspirations to work with simple geometrical configurations that can create sophisticated results. Our first attempts concentrate on fibre-optic rods (Figure 2).

Figure 2. Fibre-optic rods protrude out of movable rectangular frames.

4. Re-thinking Media Wall

Our media façade, Tran[s]quillity, will be similar to conventional LED media façades only in the way that it will consist of individual panels. The panels will aggregate to create a larger single screen. This single screen will function as a flat display surface when desired. However, each individual panel will have the capability to sweep about two axes to create motion. We are aiming to use this motion to generate *dance* choreographies and geometrical configurations (Figure 3). The panels will be capable of displaying content while moving, so the choreographies can be designed by taking both capabilities (rotational actuation and displaying) into account. When the display screens are off, the façade can become a pixelated pattern.

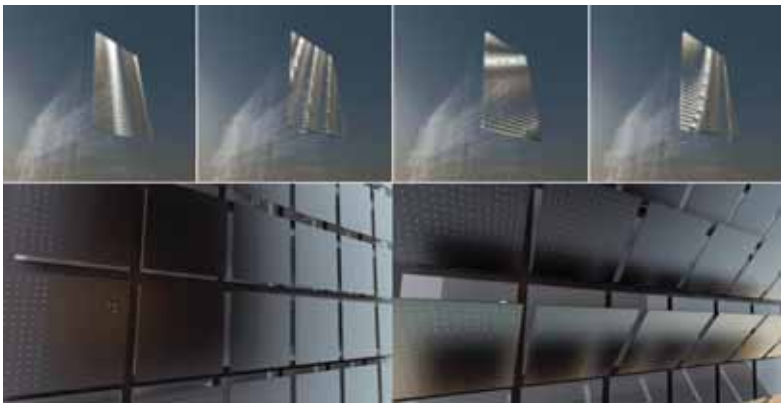

Figure 3. Choreographed panel rotations create 'textures' on the façade.

5. Design Objectives

Pandora is planned to be an environmentally conscious building. It aims to incorporate state of the art sustainability technologies. The media façade should represent Pandora's originality as well as its environmental sensibilities.

The Pandora media façade should allow for a wide range of content to be expressed *by* its surface. As the screen itself must reflect Pandora's originality and sensibility, so should the screen's content. It should welcome people at the threshold of the City of Venice. The content and the actuation of the façade should be integrated together to hold the potential to transmit ever-changing messages on any given day (Burnett, 2004).

The Media façade should be visible to passers-by whether they are on foot, in a car, or on a train, even under the broad daylight. The façade should be similarly priced

as a standard LED screen and last for a long time. Construction and maintenance should be feasible. Energy consumption should be one of the main concerns. The photo-voltaic panel array on the roof of the building should be used as one of the energy resources for operation of the installation. The media wall should be easy to implement and it should utilize existing technologies. Finally, the media wall should in itself be optically complex and intriguing, even when no image is displayed.

5.1. ENGINEERING ASPECTS

- Screen Size and Shape: The screen must be high enough on the wall that it is not obscured by the surrounding trees and structures. Using a standard aspect ratio (such as 4:3 or 16:9) will allow a greater range of media content that can be efficiently displayed. If the full width of the wall is used for the long dimension of the screen, the screen will be 16m X 9m, or 144m2.
- Resolution: One of our fundamental concerns is the resolution of the media façade, to enable legible text display over the span of the screen. A regular definition screen has 43,000 pixels and a high definition screen has 60,000 pixels ("**Outdoor LED Screens, LED Displays** and Advertising Signs", 2010). Many large media screens have a larger number (150,000 or more) of pixels to increase the brightness of the screen as well as to decrease the minimum viewing distance at which the screens pixilation is no longer apparent (GKD, 2011). For a high definition screen that is 144m^2, the minimum distance between pixels should be 5.4cm in both the vertical and the horizontal directions.
- Brightness: The minimum brightness of a screen that is visible in daylight is 2000 cd/m^2, and up to 5000 cd/m^2 if it is to be viewed in direct sunlight ("**Outdoor LED Screens, LED Displays** and Advertising Signs", 2010). Our façade faces mostly north which will limits its exposure to direct sunlight (with exceptions only during sunrise and sunset during parts of the year), making 2000 cd/m^2 a sufficient amount of brightness.
- Viewing Distance: The minimum viewing distance for a screen that is 16mX9m will be on the order of 35m ("**Outdoor LED Screens, LED Displays** and Advertising Signs", 2010). For the Pandora building this means that, if the screen is atop the building, centre of the screen will already be at 24m; the screens should be viewable to any person 24m away from the building.
- Screen Technologies: The screen technology must balance the many design objectives ranging from originality to cost. This is discussed below in greater detail.

5.2. ANALYSIS OF SCREEN TECHNOLOGIES

We investigate the properties of LED panels as well as two other technologies. One competing technology is the Mediamesh LED screen manufactured by GKD in the UK. This media façade suspends LEDs on a transparent wire mesh. These

Table 1. Key Properties of Competing Screen Technologies.

		Estimated Cost	Weight [Kg]	Resolution	Brightness [cd/m2]	Min Viewing Distance [m]	Lifetime [yrs]	Power Consumption [kW]	Yearly power costs [$/year]	Ease of Implementation [0-9]	Ease of Changing Media [0-9]	Originality [0-9]	
16m by 9m	Mediamesh LED	$700K	864	High	2K-6K	20-50	10	5	9125	9	9	7	
	LED Display	$250 -$400K + Inst.	12400	Higher	2K-10K	20-50	10	7	12775	9	9	3	
	Projection	$500K+ Inst.	0	Very High	2000	20	35	40	73000	0	0	9	
15.75m by 28m	15.75m:28m												
	Mediamesh LED	$2100K	2592	High	2K-6K	20-50	10	15	27375	9	9	7	
	LED Display	$750 -$1200K + Inst.	37200	Higher	2K-10K	20-50	10	21	38325	9	9	3	
	Projection	$1500K+ Inst.	0	Very High	2000	20	35	120	219000	0	0	9	
	Mediamesh LED	0	1	-1	-1	0	0	0	0	0	0	1	0
	LED Display	0	0	0	0	0	0	0	0	0	0	0	0
	Projection	0	1	1	-1	1	2	-2	-2	-2	-2	2	0

screens feature a low surface weight and benefit from reduced wind loads (GKD, 2011). The transparency of the screen opens up the potential to use the space behind the screen as another design parameter. The other competing technology employs the movie theatre projectors (at 30,000 lumens a piece).

We compare the potential core technologies to a standard LED panel screen (Table 1). These results are inferred and scaled from other projects using similar technologies or are taken from manufacturer specifications. The dimensional numbers are collapsed into a Pugh chart in the second table, which allows us to holistically compare the technologies.

In summary, the installed cost of the screen will likely be similar independent of the technology employed. The competing technologies weigh less than LED panels, and while the maximum resolution of the media mesh is slightly less than an LED screen (though sufficient for high-definition) the resolution of the movie projectors is unparalleled. The LED screens, both panel and mesh, are expected to last 10 years, while the projectors will likely last comparatively more with proper maintenance. However, the projectors will consume 8 times the amount of power of an LED screen of similar brightness. The environmental impact of the projectors' inefficiencies is reflected in the large annual energy cost. The projectors are also more complex to install. Custom engineering will be required to integrate multiple projectors, and an external housing will be necessary for their accommodation. Digital projectors for large scale projections are available on the market, but they are three times more expensive. Finally, the projectors' brightness falls short of 2000 cd/m^2, a number easily achieved and surpassed with either of the LED screens.

6. Mechanical and Architectural Simulations

We worked with digital models of Tran[s]quillity in various software platforms. We built a four panel CAD model in Solidworks and used it to simulate panel motions. These simulations helped us to address some crucial questions: if the panels are powered on, and we are not able to obtain feedback on each panel's position (as is the case with conventional servos) how can we safely move the panels into a known state without making them collide? In building the ¼ scale prototype we identified a sequence that allowed for a safe recovery motion sequence from an unknown state. How far apart do the panels need to be spaced so that they do not hit each other? We found that the minimum spacing was on the order of the thickness of the panels, so that each panel could tilt forward without hitting the panels above and below it.

The models we built in Rhinoceros 3D and 3DS Max helped animate the panel kinematics. We used parametric modelling and scripting tools of these software platforms. In these models we included the whole VEGA site, Pandora building and all of the 432 panels, modelled in real-world scale.

We animated our media façade using bitmap RGB values extracted from images and videos. We worked with MAXScript to use the RGB and grey-levels values of individual pixels to determine the degree of rotation for corresponding panels. The resulting motions were rendered under realistic natural lighting conditions which helped us simulate the visual effects that could be achieved by a kinetic screen at the gateway of City of Venice (Figure 4). Animations shot from virtual cameras placed in street level gave us ideas about the perceptual qualities of the wall when observed from below. Although the depth created by the panels are planned to be a little more than 1 meter, the animations and renderings reveal the visibility and potential success of aimed effects.

Figure 4. Tran[s]quillity in motion: A frame from our animation reveals the potential visual effects that will be achieved.

7. Scale Prototype, Real Scale Considerations, and Further Development

Our ¼ scale prototype consists of four panels (Figure 5). Each panel is mounted to a servo controlled (Hitec HS-985MG high torque) pan and tilt mechanism (ServoCity SPT200H) that allows it to rotate about two axes. The servos are controlled by a microcontroller (Pololu Maestro 24 Channel) which stores scripted modular dance routines that are set into play by integrated motion sensors (triggered by passers-by). The dance routines are programmed using a scripting language (Maestro Scripting Language, Pololu Robotics) on a PC and transferred to the microcontroller via a USB cable.

As the overall envelopes of motion for each panel intersect in space, each panel should be informed about the position of the neighbouring panels. In the prototype this was achieved by specifying dance routines that carefully avoided collisions. We were able to create a variety of strictly specified motions by creating modular dance routines (Figure 6).

Figure 5. The ¼ scale prototype features 4 servo-actuated 4 panel which we can perform various rotational choreographies.

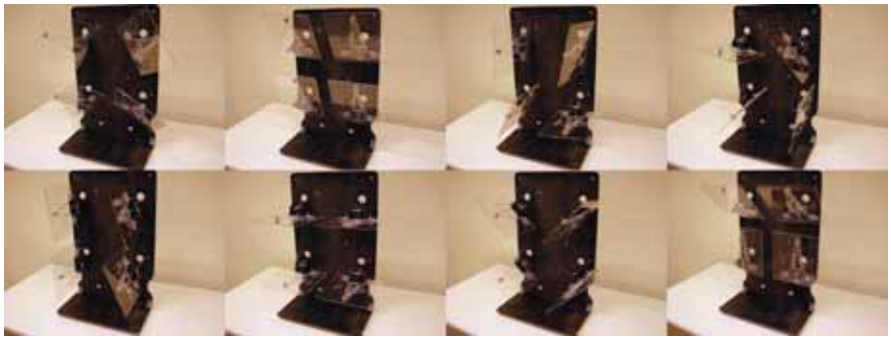

Figure 6. Screenshots from the video of Tran[s]quillity prototype dance sequence.

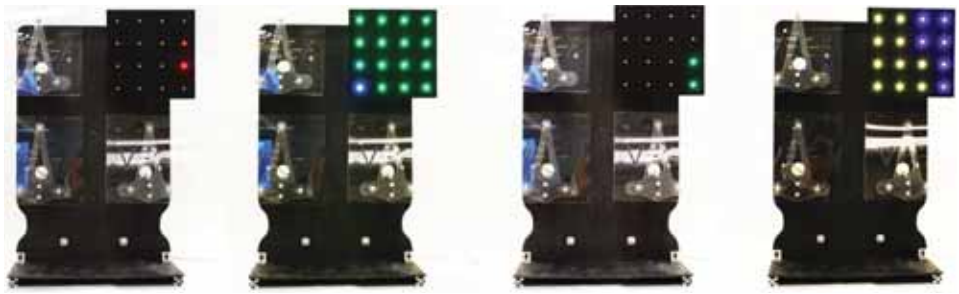

Figure 7. A 25cm by 25cm 16-LED light panel shown on our ¼ scale prototype. Actual full scale panels will measure 1 meter on one edge and will feature 100 LED lights.

Limiting the starting and ending configurations of each dance allows the dances to be strung together in any sequence. We can combine swift and slow manoeuvres with tightly controlled velocities and accelerations. In the future we are planning to simulate each panel's motion envelope and develop a program to avoid self-collisions.

Later in the process we replace the laser-cut placeholders with small LED panels that feature 16 LED lights to demonstrate the display functionality of our wall (Figure 7).

The prototype provides the requisite intuition that must be obtained before designing and building a full scale façade. The prototype was not designed for the rugged requirements of a building façade in a windy climate with salt in the air. In the final embodiment, light-weight-mesh panels that are easy to move and have a low wind load, such as Mediamesh (GKD, 2011), can be used. Changing the actuators with fewer parts than servo motors will increase the durability of the construction and a parallel mechanism would provide more strength than a serial mechanism. These objectives could be met with parallel pneumatic or hydraulic actuators.

8. Contributions

In our project Tran[s]quillity, we propose a dual-function media façade: we merge a kinetic sculpture with a high-resolution display screen.

To achieve our goals we use emergent design techniques and carry the line of research via taking both the architectural and mechanical engineering considerations into account.

We do not merely rely on computational simulations. We build a fully-functional prototype. Our scale prototype becomes the proof of our concept, and it helps us to determine the potentials and limitations of our proposed system.

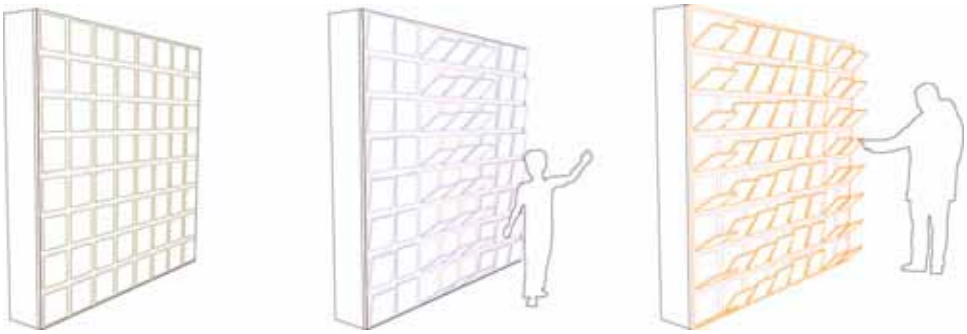

Figure 8. Conceptual images for a smaller scale build inspired by our prototype: Tran[s]quillity responding to passers-by.

In the future development of Tran[s]quillity, we see interactivity to become the key concept to be studied. Once set as a fully functional interactive wall with environmental sensors, Tran[s]quillity can become an interface to connect the interior and the exterior of building Pandora. (Figure 8).

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References

Borras, M.: 2010, *Light innovations*, Loft Publications, China.

Burnett, R.: 2004, *How images think*, MIT, Cambridge, MA.

GKD: 2011, "Mediamesh Brochure". Available from: Open Source Repository <http://www.medienfassade.com/> (accessed 28 November 2011).

Haeusler, M. H.: 2009, Media-Augmented Surfaces: Embedding Media Technology into Architectural Surface to Allow a Constant Shift between Static Architectural Surface and Dynamic Digital Display, *Computation: The New Realm of Architectural Design*, eCAADe, Istanbul, 483-490.

Heidjens, S.: 2010, "Shade". Available from: Open Source Repository <http://www.simonheijdens.com/shade/> (accessed 20 November 2011).

"Outdoor LED Screens, LED Displays and Advertising Signs": 2010. Available from: Open Source Repository <http://www.displaysled.com/products/outdoor/> (accessed 30 November 2012).

R. Stouffs, P. Janssen, S. Roudavski, B. Tunçer (eds.), *Open Systems: Proceedings of the 18th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2013)*, 965–974. © 2013, The Association for Computer-Aided Architectural Design Research in Asia (CAADRIA), Hong Kong, and Center for Advanced Studies in Architecture (CASA), Department of Architecture-NUS, Singapore.

AUGMENTING PUBLIC SPACES WITH LIVE FORMS AND FABRICS

Integrating mechatronics and textiles to provoke social interactions in public spaces

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Abstract. The research reported in this paper aims to investigate the potential of integrating live forms and fabrics to enable social interactions at existing public sites as a brief for a transdisiciplinary student design project. Through the use of flexible and modular design and fabrication methods, mechatronics, and smart materials and textiles, existing public sites were augmented with interactive installations by groups of students coming together from multiple cognate design disciplines spanning public art to engineering and including textile design.

Keywords. Interactive architecture; textiles; microelectronics; full-scale prototyping; public space.

1. Introduction

> *"Each person, withdrawn into himself, behaves as though he is a stranger to the destiny of all the others. His children and his good friends constitute for him the whole of the human species…And if on these terms there remains in his mind a sense of family, there no longer remains a sense of society"* (de Tocqueville, 1840).

The problem of the 'Fall of Public Man' (Sennett, 1976), linked particularly to the competitive, status-anxious, capitalism of the new world was the social contextual problem presented to stimulate experimental intervention in the public space by students. Combining textile and information technology we sought to make this representative of the hybrid nature of contemporary public meeting ground. In the world today, there is a new public space that is substantially virtual – Facebook,

internet blogging, Twitter but still significantly dominated by individualism and projection of the self. But there is potential to turn the same technology to more collective ends, confronting issues such as carbon and climate change that demand a broader basis for collective interaction.

As social networking and its relationship to recent political events in the world show, ubiquitous computing offers some new opportunities for linking people to one another and linking people to all sorts of data. This could be gathered aggregated data, or real time local data collected through sensing technology, or crowd-sourced social data input via mobile devices etc. The advent of cheap and easily accessible microelectronics that no longer require specialist knowledge or expertise to deploy them, smart-materials, from light and heat responsive pigments to embedded electronics, and new textile design technologies present an interesting palette to novice designers looking at the potential to augment the social space in virtual and material ways. Textile practitioners are combining digitised techniques with traditional 'analogue' versions, and using new materials to create pattern and form that are beyond the merely decorative (Braddock Clark and Harris, 2012).

We targeted the design and development of prototypes, which are innovative, functional, interactive, and responsive, in order to retrofit and reactivate existing sites that were considered "dead". The project, delivered in an 8-week intensive studio that addressed the interaction between people sharing public space, their interaction with the wider community and with concealed activity such as ambient and artificial flows and events within the city. It posed the question of how textiles, computing, communication, sensing and actuation could be retrofitted to the visionary city of the immediate past to foster concurrent interaction in physical and virtual public space.

The investigations were performed through a studio, involving 35 students from six different design disciplines – architecture, landscape architecture, interior design, industrial design, textile design, and public arts – and a team of teaching staff and tutors with backgrounds in architecture, computer science, arts, textile design, and mechatronics. Students learned to design and construct architectural models using digitally fabricated models and woven, knitted, or printed textiles, embedded with smart materials. Integrated with sensors and actuators connected to embedded microelectronics, these architectural models were to respond to or interact with the changing environment or users.

This paper presents a discussion of three of the seven different prototypes that were proposed and tested during the studio. The public were given the opportunity to test the prototypes in the street over several days.

2. Methodology

The methodology sought to engender a genuinely trans-disciplinary design research space. The fundamental components were generative design, mechatronics, textile

design and smart (use of) materials. There was a broader aim to locate the design activity socially, historically and in the contemporary application of technology in design.

The trans-disciplinary design learning was first organised around introducing textile design and responsive materials. Textile fibres offer a variety of unique appearances and qualities such as translucency, colour, patterning effects, and surface texture and tactility (Salim et al., 2012). With the development of new textile fibres, such as blended fibres, microfibers, and nanofibres with high strength, low weight, and better performance than conventional materials (Horrocks and Anand, 2000), it is now possible to use a textile to achieve a structural function as well as aesthetic quality. In addition, by combining textile materials with non-textile such as sensors, actuators, processors, and microsystems (Jayaraman et al., 2006), and hybrid materials, such as microelectronic components and conductive substrates, fabrics may no longer be passive, but instead have the capacity to monitor and interact with individuals and their environment. This suggests that surface, structure and form are becoming more interconnected, interdependent and interactive, and for innovative design solutions to emerge, designers need to work beyond the traditional boundaries of their disciplinary areas (Underwood et al., 2009).

Therefore, to enable trans-disciplinary design learning in this studio, the lectures were wide ranging, from introduction to textile design and smart materials, responsive and interactive architecture and design engaging mixed reality to theoretical introduction to the history of the utopian city, the specific social and architectural history of the site. Guest lecturers introduced mechatronics, multi-criteria optimisation for performance design (the design and prototyping of the electric racing car), interactive architecture (the design and prototyping of the Aegis Hyposurface). The skills offerings were equally catholic with the expectation that the group members would naturally specialise within the group and self select which activities to focus on. Thus most participants were given support to learn parametric modelling using Grasshopper (www.grasshopper3d.com) and Yeti (www.yeti3d.com), to work with Arduinos (arduino.cc) and Firefly (www.grasshopper3d.com/profile/firefly), and other simple programming protocols while the textile participants focused specifically on textile based technologies.

Following the first week when the students developed individual conceptual proposals in order to ‘market’ their ideas to the whole group, the design was carried out in groups, each with a representative from every discipline. The textile representatives led many of the early concept discussions. They brought samples of novel two and three-dimensional textile weaves and knits to the class along with precedents for smart material development. This extended the group thinking in terms of the material performance component of their designs. To accommodate the focus of and demands of all the disciplines engaged, the groups were also

briefed to consider the project from a top-down perspective and develop a master plan for the whole of the streetscape to be engaged as the site. The material-driven bottom-up thinking and top-down master planning were engaged in parallel.

3. Projects

In this paper we explore three of the seven projects in greater detail as the basis for evaluation of the success of introducing textiles as a tactile medium with which to achieve the social interaction ends through a digitally enhanced public space.

3.1. GROUP 3: "IN-BETWEEN" ORGANIC ROBOTICS

The "*In-between" organic robotics* project examined the integration of textiles and technology as a platform to encourage social interaction through a sensory experience. It used soft shell architectural membrane to create a sense of protective intimacy and encourage the user to actively engage with their surrounds through touch and sight. The space represented "our lived memories, imagination, fantasies and dreams" (Group 3 et al., 2011).

The skin of the space is made up of multi-layered materials. The outer surface is a highly elastic fabric, printed with a pattern of organic line-work referencing a biological system. The fabric's fine gauge jersey knit construction enables a high degree of stretch and recovery, semi transparency when stretched, creating a dimensionality of shadows cast by the opaque line-work and the fine lace-like lattices that were laser cut from the same flexible knitted material and layered within the structure's walls. The pattern was printed on both sides of the fabric, so that the pattern appears to float across and through the surface moving in and out of focus. The sensory experience is further heightened through the use of thermo-chromic pigments. At 30 degrees and above, these heat-sensitive pigments lose their colour, so when the user touches the surface the pattern dissolves and leaves a momentary imprint of their presence. As the temperature decreases, the pattern again returns. Embedded in the surface are sensors that detect the users' presence and activate coloured lighting in the space through the use of arduinos.

The prototype was tested at street level (Figure 1) but conceived for an underground passage under one of the road intersections on the site (Figure 2).

This project succeeded well at engendering both intimacy and user fascination at the level of detailed interaction where the heat sensitive textile and motion sensitive lighting proved robust forms of actuation. The challenge of integrating this highly interior architecture into the public realm and tensions between public and private forms of movement and behaviour were less easy to resolve.

Figure 1. "In between" organic robotic project prototype being tested on the public street by day and by night.

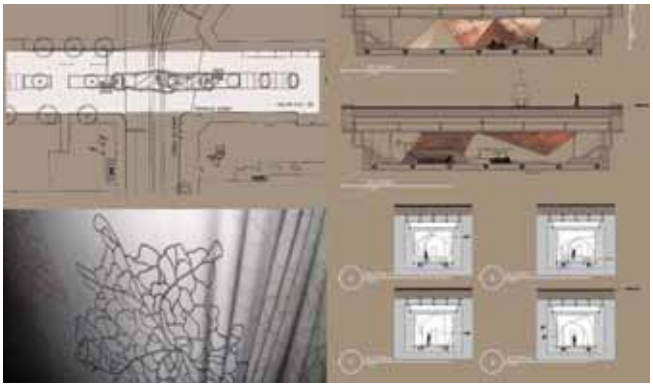

Figure 2. "In between" organic robotic project – site plan and sections showing the intention to create an underground linking tunnel to be lined in this way; heat sensitive print on surface that dissolves on contact.

3.2. GROUP 4: BIOMIMICRY

The *Biomimicry* project investigated the potential of a textile to act as both a form-building device and a flexible, sensor-driven model to communicate ambient environmental states.

For the installation, the initial inspiration was drawn from coral patterns and geometries, as a means of achieving an organic structure with kinetic qualities. These structures act as an agent, highlighting and distinguishing the levels of complexity within the overall system (Group 4 et al., 2011).

Initial experimentation by the textile design student developed a system of weft knitted peaks and cut-outs (voids), utilising various 3D shape knitting techniques,

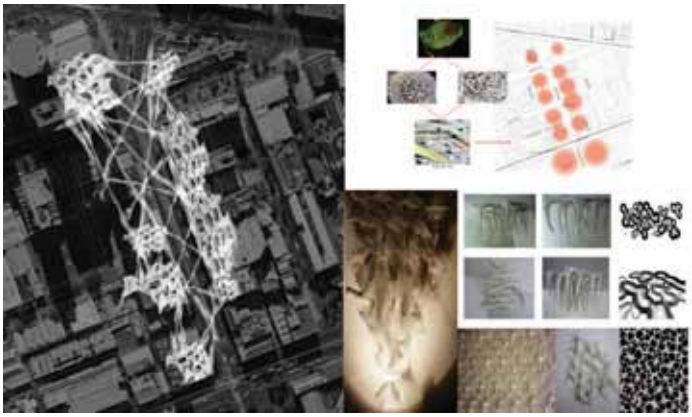

Figure 3. Biomimicry – masterplan , installation sites and textile experiments.

such as holding stitches and short row patterning (Figure 3). Being an additive fabrication process, weft knitting offers the advantage of being able to tailor (shape), through the deliberate placement of stitches and holding of stitches, complex surfaces and 3D forms using one continual thread. Such an approach enables the opportunity to explore electronics such as feeding light or fluid through a tubular "thread" in the knit.

From these knitted samples, the group then developed a series of small physical and digital models to examine the responsive potential of the knitted samples. Real time data on carbon dioxide levels and levels or other pollutants were fed to the system and calibrated to trigger the release of different coloured fluids into the tubes so that the whole knitted 'organism' would alter its spectral state in a way drawing on the metaphor of coral bleaching or adaptive colouring in frogs or polychrotidae.

Hand knitted, using packaging tubes as giant 50mm diameter needles, the full scale piece was knitted from one continuous length of clear plastic tubing that was both flexible and stable. The ends of the tubing were then connected to the pump to circulate the fluorescent fluid through the piece as a continuous system. A system of kiragami inspired peaks, made from lycra were laser cut in a pattern derived from self-organisation. Conceptually while the knit would festoon identified locations throughout the site it was also conceived as a social environmental statement that could grow and recede over time, inspired in part by the Croquet Coral Reef (Wertheim, 2009).

This project exhibited conceptual strength as an environmental barometer and interesting opportunities to adapt textile formats but was very challenging to realise as a full-scale prototype (Figure 4), using materials that do not conform to

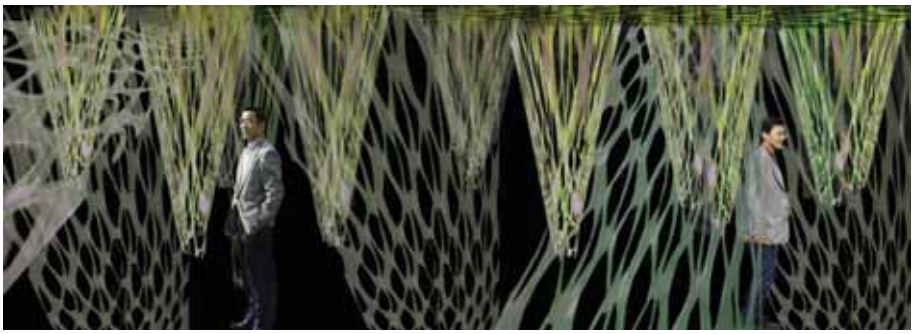

Figure 4. Biomimicry – concept render for the full scale installation.

existing textile technologies and missible fluids with unpredictable characteristics. It was also more difficult to evaluate public impact without installing a robust long-term intervention.

3.3. GROUP 7: THE TUNNEL VISION EXPERIMENT

The *Tunnel Vision* group's initial response was to collect a body of detailed information from the site. Through discussions, in the context of their precedent topics of translucency and blur, the group asked themselves 'how do we set up a public responsive intervention to blur the boundaries between sets of users?' (Group 7 et al., 2011). These discussions led the group to focus on human movement and the idea of layered, adaptive translucency. An installation was proposed with multiple layers of translucent screens that would be fixed to a minimal frame.

The patterning and graphics for the fabric panels drew inspiration from the surroundings of the site, specifically the Swanston Street Axis (the principal central axis through Melbourne) central to the site. The patterning used a geometric abstraction referencing the on–axis Shrine of Remembrance and the circular disc motif of the facing on-axis Design Hub building. The simplified geometric patterns provided an added detail to the surface, and a sense of depth and transition through the play of light and casting of shadows.

The panels being of a lightweight semi-transparent thermoplastic fabric were digitally printed, heat set and laser cut and then layered. Within the floor of the installation a system of pressure sensors were embedded using arduinos to activate servo motors to swing the translucent screens open in a 'Mexican wave' along the tunnel in response to passing footfall (Figure 5). This enabled the screens to adjust automatically to human motion detected beneath it through tracking movement. The printed patterns on the screens animate in the manner of a flipbook (Figure 6).

Figure 5. Tunnel Vision – render of the tunnel in use.

Figure 6. Tunnel Vision – large scale prototype on the street showing the flip book use of printing on the fabric. Top right insert early experiments with translucent fabric.

The challenge of actuating large swinging screens in response to pedestrian foot fall was much greater than in some of the other projects. The integration of textile printing was a powerful communication idea in the site.

4. Conclusion

The challenging combination of novel textile applications with microelectronics to link ambient and external data to interactive prototypes was a very successful vehicle for a transdisciplinary design studio that engaged all the participants fully. It was also found to succeed at the level of activating the public space and engaging public participation, although the novelty of a short-term occupation and engagement may have contributed to this aspect. The students included ethnographic film studies and records of participant interaction in their research before, during and after the installation of the prototypes in the public space. The focus on textiles was a key component in the studio which drew the students from disciplines other than textiles in through early tactile concrete engagement with material systems, form and performance properties.

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References

Braddock Clark, S. E. and Harris, J.: 2012, *Digital Visions for Fashion and Textiles; made in code*, Thames and Hudson, London.

de Tocqueville, A.: 1840, *Democracy in America*, 2nd vol.

Group 3, Black, T., Kapsis, M., Leung, S., Siswandi, I. and Tran, L.: 2011, Organic Robotics Portfolio, unpublished PDF file, Augmented Spatiality Studio, RMIT University, Melbourne.

Group 4, Yi, C. Y., Xiao, E., Ianni, A. and Henke, K.: 2011, Biomimicry Portfolio, unpublished PDF file, Augmented Spatiality Studio, RMIT University, Melbourne.

Group 7, Guest, D., Fouche, L., Fleming, B. and Bujnowski, T.: 2011, Tunnel Vision Portfolio, unpublished PDF file, Augmented Spatiality Studio, RMIT University, Melbourne.

Horrocks, A. R. and Anand, S. C. (eds.): 2000, *Handbook of technical textiles*, The Textile Institute and Woodhead, Cambridge, UK.

Jayaraman, S., Kiekens, P. and Grancaric, A. M. (eds.): 2006, *Intelligent Textiles for Personal Protection and Safety*, IOS, Amsterdam.

Salim, F. D., Burry, J. R., Peers, J., and Underwood, J.: 2012, Augmented Spatiality, in *International Journal of Architectural Computing* **10**(2), 275–300

Sennett, R.: 1976, *The Fall of Public Man*, Knopf.

Underwood, J., Lynas, E., Adams, L. and Beale, C.: 2009, Transformative Textiles, *Cumulus 38° South 2009, Proceedings of the Cumulus Conference*, Melbourne, Australia.
Wertheim, M.: 2009, "The Beautiful math of coral". Available from: <http://www.ted.com/talks/margaret_wertheim_crochets_the_coral_reef.html> (accessed on 12 December 2012).

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