

CIRCUIT BENDING, BREAKING AND MENDING
Proceedings of the 16th International Conference on Computer-
Aided Architectural Design Research in Asia (CAADRIA 2011)

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Circuit Bending, Breaking and Mending
16th International Conference on Computer-Aided Architectural Design
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FOREWORD

The annual CAADRIA (Computer-Aided Architectural Design Research in Asia) conference provides an international community of researchers and practitioners with a forum to exchange and publish their latest ideas and accomplishments. This volume contains 72 papers that were accepted for presentation at the 16th International CAADRIA Conference, hosted and organised by the School of Architecture and Built Environment at The University of Newcastle, Australia. 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 was produced by a motivated team of volunteers through an extensive collaborative process, and it testifies to CAADRIA's increasingly respectable standing.

Calls for papers in mid-2010 resulted in the submission of 182 abstracts. These were initially reviewed by the paper selection committee, who invited 140 abstracts for further development. Of these, 89 full papers were submitted to the final review stage. A double-blind review of each paper was carried out by two to three international reviewers. Following their recommendations, 78 papers were finally accepted for publication. We congratulate the authors for their accomplishment.

Next to the authors, the reviewers, all of which volunteered valuable time and effort, deserve our sincerest acknowledgements. Moreover, we owe particular gratitude to the conference organisers and to the conference host for their generosity and dedicated work. We also express our deep gratitude to the current CAADRIA president Andrew Li for his vital contributions to the production of this and of last year's CAADRIA proceedings. On the following pages, we acknowledge and thank those who contributed to the production of this volume.

We congratulate Julio Bermudez, who, in recognition of his outstanding contributions to research in our field, received CAADRIA's 2010 Sasada Award. During the time leading up to this conference, one of CAADRIA's founding members, Milton Tan, passed away at an untimely age. He is missed dearly. Together with the National University of Singapore, CAADRIA recently established a scholarship in his memory.

In closing, we sincerely thank the CAADRIA community for offering us the honour to serve as members of the paper selection committee for CAADRIA 2011.

C.M. Herr, N. Gu, S. Roudavski and M.A. Schnabel (editors), April 2011

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FORUM8

TABLE OF CONTENTS

Foreword	i
Circuit bending, breaking and mending: Editorial introduction <i>C. M. Herr, N. Gu, S. Roudavski, M. A. Schnabel</i>	1
Generative and parametric design I	
01. One-piece weaving: Reconfiguring folding and knotting algorithm in computational design <i>Rizal Muslimin</i>	9
02. Analysis model for incremental precision along design stages <i>Marcelo Bernal</i>	19
03. The flexibility of logic programming: Parametrically regenerating the Sagrada Família <i>Daniel Davis, Jane Burry and Mark Burry</i>	29
04. Parametric modelling and design processes: Exploring synthesis and evaluation using a Function-Behaviour-Structure perspective <i>Benjamin P. Coorey and Julie R. Jupp</i>	39
05. Computational landscape design with the seed scattering system: A case study in the Sony forest project <i>Aya Okabe and Tsukasa Takenaka</i>	49
Generative and parametric design II	
06. Digital catalogue: A computational implementation of Korean joinery system in the design of a transformable disaster shelter <i>Jason J. Kim and Hyoung-June Park</i>	61
07. Digital tea house: Japanese tea ceremony as a pretext for exploring parametric design and digital fabrication in architectural education <i>Kaon Ko and Salvator-John Liotta</i>	71
08. A new perspective to look at ice-ray grammar <i>Xiaofang Yuan, Ji Hyun Lee and Yu Wu</i>	81

09. Form follows parameters: Parametric modeling for fabrication and manufacturing processes 91
Jonathon Anderson and Ming Tang
10. Supporting shape reinterpretation with eye tracking 101
Iestyn Jowers, Miquel Prats, Nieves Pedreira, Alison McKay and Steve Garner

Generative and parametric design III

11. Affordable, performative and responsive: Designing affordable responsive architectural prototypes through physical and digital modelling 113
M. Kamil Sharaidin and Flora Dilys Salim
12. Searching generative methods based on building environments 123
Biao Li and Rong Li
13. Graph visualization in computer-aided design: An exploration of alternative representations for GenerativeComponents™ Symbolic View 133
Karine Kozlova, Roham M. Sheikholeslami, Lyn Bartram and Robert F. Woodbury
14. Designing elastic transformable structures: Towards soft responsive architecture 143
Chin Koi Khoo and Flora Dilys Salim

Generative and parametric design IV

15. Designing responsive architecture: Mediating analogue and digital modelling in studio 155
Daniel Davis, Flora Dilys Salim and Jane Burry
16. Parametric materiality: Material properties as catalyst for design 165
Russell Loveridge
17. Tree facades: Generative modelling with an axial branch rewriting system 175
Stuart Hanafin, Sambit Datta and Bernard Rolfe

Virtual and interactive environments I

18.	Understanding and constructing shared spaces for supporting informal interaction at a distance	189
	<i>Thi Lan Truc Nguyen and Beng-Kiang Tan</i>	
19.	A context immersion of mixed reality at a new stage	199
	<i>Juhyun Lee and Mijeong Kim</i>	
20.	Three-dimensional computational structures and the real world	209
	<i>Werner Lonsing and Peter Anders</i>	
21.	Real time modelling: A solution for accurate, updatable and real-time 3D modelling of as-built architecture	219
	<i>Russell Lowe, Jules Cromarty and Richard Goodwin</i>	
22.	Real-time porosity: Combining a computer game engine with environmental sensors to better understand pedestrian movement in public/private space and in real-time	229
	<i>Russell Lowe, Mark Hedley and Richard Goodwin</i>	

Virtual and interactive environments II

23.	Indirect biofed architecture: Strategies to best utilise biofeedback tools and interaction metaphors within digital architectural environments	241
	<i>Erik M. Champion and Andrew Dekker</i>	
24.	Preliminary experiments of OPENSIM performance evaluation for virtual design studios	251
	<i>Walaiporn Nakapan and Ning Gu</i>	
25.	Simulating 3D architecture and urban landscapes in real space	261
	<i>Shun Watanabe</i>	
26.	First steps of the augmented design studio: The interconnected Hybrid Ideation Space and the CI Loop	271
	<i>Tomás Dorta, Yehuda Kalay, Annemarie Lesage and Edgar Pérez</i>	
27.	Interaction in terms of individuality and intelligibility	281
	<i>Hao Hua and Ting-Li Jia</i>	

Virtual and interactive environments III

28. Two conceptual design tools and an immersive experience:
Beyond the pragmatic-pleasurable split in UX 291
Annemarie Lesage and Tomás Dorta
29. Active buildings: What can we do about buildings that
simply stand still? 301
Yasu Santo, John H. Frazer and Robin Drogemuller
30. Mirrored message wall: Bridging the real and virtual community 311
Beng-Kiang Tan and Jung-Ho Yeom
31. A study of variation of normal of polygons created by point
cloud data for architectural renovation field 321
Tomohiro Fukuda, Kensuke Kitagawa and Nobuyoshi Yabuki

Ubiquitous computing

32. Last train to Trancentral: From infrastructure to 'info'structure:
a case study of embedding digital technology into existing
public transport infrastructures 335
*Tom Barker, Nicole Gardner, M. Hank Haeusler and Martin
Tomitsch*
33. Second-order prosthesis: Human-aided design within the
expanded field of ecology 345
Tina A. Salama
34. SMAAD Surface: A tangible interface for smart material
aided architectural design 355
Akira Wakita, Akito Nakano and Michihiko Ueno
35. Architectural creativity in commercialised cyberspace 365
Stanislav Roudavski and Sonya Parton
36. A work service model of the ubiquitous office 375
Heehwa Chae, Mijeong Kim, Juhyun Lee and Xiangyu Wang

Design cognition

37. An ontology representing Roberto Burle Marx's landscape design solutions 389
Carlos V. Vaz, Gabriela Celani and José P. Duarte
38. CAD software as customisation tools: Using FBS protocol coding scheme to understand the behaviour of mass customisers 399
Morteza Pourmohamadi, John S. Gero and Robert Saunders
39. Rethinking concept design tools: High-level requirements for concept design tools 409
Volker Mueller and Ivanka Iordanova
40. The polymorphic diagram: On mediating spatial thinking in architecture design 419
Qutaibah Hamadah
41. Assessment of design tools for ideation 429
Edgar Pérez and Tomás Dorta

Computational design analysis I

42. Complex adaptive residential quarter planning using multi-objective optimization: An agent-based modeling approach 443
Seongki Lee and Ludger Hovestadt
43. Applying interpretation-driven association to design domains 453
Kazjon S. Grace, Robert Saunders and John S. Gero
44. Exploiting instability: Reconfiguring digital systems 463
Linda Matthews and Gavin Perin
45. Computational method for mapping quality of architectural space 473
Aswin Indraprastha and Michihiko Shinozaki
46. The territory of the personal workspace: Development of the PWAS (personal workspace analysis system) 483
Mariko Enoki, Yoichi Hanada, Yuji Matsumoto, Nagisa Kidosaki, Ryusuke Naka and Shigeyuki Yamaguchi
47. Data flow and processing in the computational fractal analysis method 493
Michael J. Ostwald, Josephine Vaughan and Stephan K. Chalup

Computational design analysis II

48. Digital forensics as a tool for augmenting historical architectural analysis: Case study: The student work of James Stirling 505
Nicholas Webb and Andrew Brown
49. Towards morphogenetic assemblies: Evolving performance within component-based structures 515
Daniel Richards
50. Closing the loop of design and analysis: Parametric modelling tools for early decision support 525
Bianca Toth, Flora Dilys Salim, Robin Drogemuller, John H. Frazer and Jane Burry
51. Topology pattern mining: A visual approach for representing and retrieving design patterns of spatial topology in a case library 535
Chieh-Jen Lin
52. Assessing innovation in hybrid designs using shape grammars 545
Dhuha A. Al-Kazzaz and Alan Bridges
53. Agent-agent interaction as a component of agent-environment interaction in the modelling and analysis of pedestrian visual behaviour 555
Arash Jalalian, Stephan K. Chalup and Michael J. Ostwald

Computational research in design education

54. Gains, losses and limitations in designing parametrically: A critical reflection of an architectural design studio in China 569
Christiane M. Herr
55. The Headspace project: Computer-assisted fabrication as an introduction to digital architectural design 579
Stanislav Roudavski and Anne-Marie Walsh
56. The social network virtual design studio: Integrated design learning using blended learning environments 589
Marc Aurel Schnabel and Jeremy J. Ham
57. Thinking through digital simulation tasks in architectural education 599
Matthew Fraser and Michael Donn

58. Impact analysis of digital-based architecture curriculum on students' learning 609
Rabee M. Reffat

Theory, philosophy and methodology of computational design research

59. One-behind-the-many metaphysics and the myriad things 623
Thomas Fischer
60. Constructive interpretation with examples from interpretation of floor plans 633
Nick Kelly, John S. Gero and Robert Saunders
61. The gardens revisited: The link between technology, meaning and logic? 643
Gabriela Celani, José P. Duarte and Carlos V. Vaz
62. Architectural space information scale: A new way of understanding architectural space 653
Wei Zhang and Yiping Wang
63. A is B, displacement: Exploring linking patterns within metaphor in the design process 663
Chia-Hui Lo, Ih-Cheng Lai and Teng-Wen Chang

Computer-supported design collaboration

64. Memo Externalizer: Support environment for bridging from personal ideas to group discussions in design meetings 677
Yuji Matsumoto, Yusuke Okada, Nagisa Kidosaki, Ryusuke Naka and Shigeyuki Yamaguchi
65. The role of collective intelligence in design: A protocol study of online design communication 687
Mercedes Paulini, Mary Lou Maher and Paul Murty
66. Motivation, cyberworlds and collective design 697
Kathryn Merrick, Ning Gu, Muhammad Niazi and Kamran Shafi
67. Colour-code models: The concept of spatial network 707
Paulina Neisch

68.	Packing the “Chinese box”: A strategy to manage knowledge using architectural digital models <i>Simone Garagnani</i>	717
Design intelligence and automation		
69.	Using domain specific languages in the Building Information Modelling workflow <i>Ruwan Fernando, James Steel and Robin Drogemuller</i>	731
70.	Digital manga depiction <i>Marc Aurel Schnabel and Yingge Qu</i>	741
71.	Structural form generation using interactive genetic algorithm <i>Weixin Huang, Weiguo Xu and Tao Wang</i>	751
72.	Daylight and energy in the early phase of architectural design process: A design assistance method using designer’s intents <i>Mohamed-Anis Gallas, Didier Bur and Gilles Halin</i>	761
	Author index	773

CIRCUIT BENDING, BREAKING AND MENDING

Editorial introduction

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After 10 years, this year's CAADRIA conference returns to Australia, where it is hosted by the School of Architecture and Built Environment of The University of Newcastle, Australia. The two calls for papers issued for CAADRIA 2001 (then hosted by The University of Sydney), and CAADRIA 2011 bracket a captivating decade of CAAD research that allows insights into the gradual development of interests, concerns and future expectations of researchers working in the field of Computer Aided Architectural Design Research. A review of the topics in these calls for papers shows how some topics draw sustained attention. Such topics include human-computer interaction, generative design and computational analysis. Other topics stand out as new additions to the CAAD research repertoire. These are worthwhile to mention here since they indicate directions into which CAADRIA is likely to develop in its future. Among these new additions are digital art and new media, interdisciplinary computational design research as well as theory, philosophy and methodology of computational design research. Taken together, these new topics indicate a broadening interdisciplinary scope and a growing maturity of our field. They also highlight a renewed theoretical discourse on the relationship of design and research.

CAADRIA 2011 called for research papers addressing the theme “Circuit Bending, Breaking and Mending”. This title aimed to provoke researchers and practitioners to reflect on the epistemological dimensions of their enquiries: What works? What does not work? And how do we learn while negotiating the two? This theme acknowledges the circular nature of designerly enquiry (Glanville, 1999) that extends into CAAD research. New ways of seeing are being explored and brought forth by the realisation that computational methods, technologies and designerly thinking are interdependently giving rise to each other. Creative thought brings forth technology. Technology, in return, promises to support creative thought. Investigations into the potential of computing in this relationship hence call for holistic research approaches.

Research in the context of designing can be usefully divided into three attitudes (Frayling, 1993/94, Findeli, 1999 and Downton, 2003, pp. 2 ff.): research for design, research into design and research through design. With its interest in computational technology, CAADRIA has a long and productive tradition focused on research for (i.e. in support of) designing. As an academic research field, CAADRIA also has a long and productive tradition focused on research into (i.e. empirically studying) designing. Research through designing (i.e. practice-based design research), however, is only hesitatingly making its way into our field. The reason for our delayed adoption of this research approach seems to lie in an additional challenge that applies to practice-based research. Outcomes of research for designing can be rigorously justified by practical utility. Outcomes of research into designing can be rigorously justified by empirical evidence. Research through designing, though, can only be appreciated rigorously outside the reach of readily formalised criteria: It leads to innovative outcomes as well as to innovative standards for the critical evaluation of these outcomes. Accommodating the required openness to support such an abstract and self-referential form of scrutiny poses challenges to an annual academic conference that draws much of its weight from strict standards, unified formats and equitable procedures.

The ongoing developments outlined above seem all the more appropriate given CAADRIA’s regional basis in Asia where holistic appreciation of systemic interdependencies and self-cultivating consciousness have long traditions. These developments demonstrate that CAADRIA, now in its 16th year, has neither reached a point of saturation with respect to its topics of interest, nor has it arrived at a set of conclusively developed standards for valuing the rich and varied work conducted under its umbrella. This indicates that exciting further advances can be expected on the future path of CAADRIA, along which the present volume of proceedings represents only one step.

In this volume, several authors call for a rethinking of the discipline from

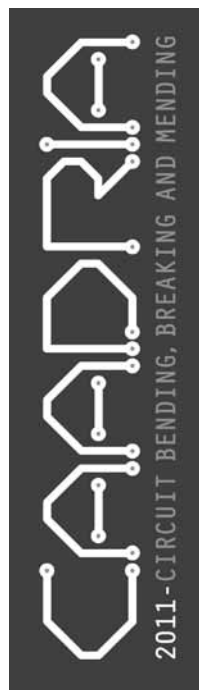
a design-based perspective, with their papers exemplifying alternative yet rigorous forms of enquiry that may inspire future developments of our field. For example, Roudavski and Parton (p. 366) observe that CAADRIA tends to exclude non-technical concerns and call for a critical discussion of digital technology with regard to its social and cultural implications. Fischer (pp. 631–632) argues that our full appreciation of designerly ways of perceiving and acting necessitates a discourse on responsibility that acknowledges the value of the personal and particular in addition to the value of the general and formal. Salama's (p. 353) work further emphasises how technological and human-centred views are symmetrically interdependent and mutually giving rise to each other.

Beyond a broadening of its scope and the deepening of its discourse, CAADRIA is taking further steps in advancing CAAD research. These include the establishment of the CAADRIA Postgraduate Student Consortium, which, now in its fifth year, supports the next generation of CAAD researchers. To sustain design-based enquiries and qualitative research approaches, CAADRIA also encourages further alternative forms of presentation, such as posters and exhibitions of artworks. These developments call for a renewed discourse on rigour in a field that should engage in, and take responsibility for, all justifiable forms of enquiry even when they extend well beyond the confines of the scientific.

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GENERATIVE AND PARAMETRIC DESIGN



GENERATIVE AND PARAMETRIC DESIGN I

01.	One-piece weaving: Reconfiguring folding and knotting algorithm in computational design	9
	<i>Rizal Muslimin</i>	
02.	Analysis model for incremental precision along design stages	19
	<i>Marcelo Bernal</i>	
03.	The flexibility of logic programming : Parametrically regenerating the Sagrada Família	29
	<i>Daniel Davis, Jane Burry and Mark Burry</i>	
04.	Parametric modelling and design processes: Exploring synthesis and evaluation using a Function-Behaviour-Structure perspective	39
	<i>Benjamin P. Coorey and Julie R. Jupp</i>	
05.	Computational landscape design with the seed scattering system: A case study in the Sony forest project	49
	<i>Aya Okabe and Tsukasa Takenaka</i>	

ONE-PIECE WEAVING

Reconfiguring folding and knotting algorithm in computational design

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Abstract. A beneficial symbiotic relationship between traditional crafts and new technologies may be achieved when computational designers view the existing traditional art and craft as partners to collaborate with and when traditional cultures are willing to accept new technologies in an enthusiastic yet critical manner. This research aims to reconfigure computational design paradigm at the intersection of traditional and digital technology by evaluating a series of relatively recent computational design experiments aimed at reconceptualizing weaving as a combination of folding algorithm and knot theory with respect to the apparent dialectical tension between traditional context and computational theories in architectural design.

Keywords. Weaving; folding; knot

1. Introduction

This research evaluates weaving mechanism as a rational artefact. In particular, we consider weaving as an assemblage of folding creases and knot's crossing points. To weave means to create a knot, and to make a knot, we need to fold. Since weaving has a rich cultural aspect in its abstraction and rationality, folding and knotting history has a strong cultural and computational background.

1.1. FOLDING

Folding ubiquity exists both in nature and culture. In nature, folding can be found in leaf mechanism, protein folding, insect wing, and many others

(Forbes, 2006; Couturier et al, 2009). In traditional culture, folding has been widely used since 794-1185 A.D. (17th century) primarily as a form of art, e.g., origami in Japan during the Heian Period (Demaine and O'Rourke, 2007). Moreover, folding is also utilized in art and technology. In contemporary design, folding has been pervasively used in architecture (Vyzoviti, 2006), fashion (Miyake, 2008), and many industrial products (Yigit, 2004). In engineering, folding is used to fold the solar sail for the satellite and safety bag for cars for its compactness as well as in shell structure for its rigidity (Candela, 1964; Engel, 1968).

1.2. KNOTTING

The ever-present knot has existed since humans first used a knot for tying a rope in hunting and clothing. In nature, birds use a knot to fasten their nests and spiders knit their webs with knots. In ancient culture, knots were physically used in numerous functions, such as textiles, huts, bridge construction, and accounting devices (khipu). Additionally, the knot is also visually depicted in many primitive symbols associated with folklore, magic, and mythology. In science and engineering, the knot has been widely scrutinized by the physicist, (Kauffman, 1987) biotechnologist, transportation engineer, electrical engineer, and many others. In today's contemporary design, the knot (like the fold) has been utilized as a main circulation concept in architectural design (e.g., Mercedes-Museum in Stuttgart by UN Studio) and tessellation in fashion design (e.g., Emily Hiller Silk Knotted Garment). Thus, folding and knotting are not unique in either traditional or computational design

1.3. PAPER CUT (KIRIGAMI)

To combine folding and knotting, we look at the *kirigami* method, a variation of origami techniques that allows paper cutting ("*kiru*" = to cut, "*kami*" = paper) (Temko, 1962). Kirigami has been commonly used for pop-ups artwork in children's books, gift wrapping, and greeting-cards. Some recent attempts to enlarge the scale of kirigami shows its promising use in architectural design, (Vyzoviti, 2010) fashion design, (Ryan, 2009) and computational biology (Harth, 2010). In Poland, the paper-cutting art has become part of their folk-art (Wycinanki) and national identity, as shown in the Poland pavilion in Shanghai 2010. Kirigami's artists have been exploring paper cutting art in both two-dimensional works such as Gjerde's Yaguchi and in three-dimensional works of art (Chatani, 1985; Badalucco, 2001). While most of these designers are using a continuous surface, kirigami can also be assembled by discrete modular elements (Hart, 2007). George Hart's *modular kirigami*

is one of the first attempts to combine paper cutting and knotting, and shall further be elaborated in this research.

Given the versatility of these three techniques in natural, cultural and computational designs, the following experiments attempt to elaborate the virtue of folding, knotting and paper cutting as parts of the weaving techniques within a mathematical model.

2. One-piece weaving

Here, we would like to compare the knots theory and folding algorithm underlying the weaving configuration. In mathematics, the knot theory studies the complexity of knots indicated by the number of crossings (Tait, 1860) and the different projections of the knot in a two-dimensional diagram (Reidemeister, 1920). With this complexity, one of the main questions in the knot theory is whether certain projected knots are equivalents (isotopic) or not. On the other hand, the folding algorithm starts by understanding the linkage behavior on a surface. Folding complexity emerged from its two simple rules, mountain and valley crease assignment, to create various linkage configurations, two-dimensional surfaces or three-dimensional polyhedral. Some of the main questions in the folding algorithm are whether the crease pattern can create a flat-foldable surface, folding without collision or generate many forms from the same shape with different crease patterns. Following are the comparison between knot and folding.

2.2. SIMILARITY: JOINTS

We first share the compatibility of the folding and knotting definition within a paper strip and its interlaced configuration. In a folding algorithm, the paper strips are considered one-dimensional (1D) *linkages*, while the segments are called *links* and the shared endpoints are called *joints*. Linkages can be open as one straight chain or closed as a convex chain where the start and end are the same (Demaine and O’rourke, 2007). In the knot theory, the convex chain paper strips are understood as unknotted links that are homeomorphic to a circle in a 3D-space (Kauffman, 1987). When we twist a rubber band for example, a knot can be seen as a crossing point resulting from the intersection of the circle perimeters where the crossing creates an over and under link condition. In other words, the knot is topologically the same as convex linkages in folding, where the *crossing* is equivalent with *joints*.

2.3. DIFFERENCE: FLEXIBILITY

Secondly, we look at two fundamental differences between folding and knot-

ting: the creases and the crossing point. Knot theory assumes the link as a flexible surface and focuses more on its crossing rather than the motion mechanism of how the flexible surface turns and bends to create the knot. In contrast, folding algorithm constrains the link mostly to a rigid surface and crossing is forbidden in folding algorithm. Therefore, folding algorithm is highly concern with the movement behavior and the directionality of the links and vertices, in which the valley and mountain crease's patterns act as an axis to control the rotational degrees of freedom of the embedded linkages on a surface.

3. Interwoven paper strip

Based on the above compatibility and differences, we use long narrow paper strips to explore folding algorithm and knot theory. Paper strips have both flexibility for knotting and surface rigidity for folding that allows us to use principles from the one-dimensional folding motion mechanism, the straight cut method, and interlocked chains. To perform a rigid interwoven joint on the paper strips, we need notches where the surface can be interlocked. Here, the notch is achieved by simply making a half-cut on the paper strip from its edge perpendicular to its axis so that two surfaces will share the half-cut as tab and notch. The main constraints in this project are the continuity of the single paper strip, which means all notches and tabs are laid out along the same surface (Figure 1).

We assume that all notches and tabs can be made in one single cut. In particular, we are interested to find out how to fold the paper strip into the shortest segment possible but long enough to create the least minimum half-cut pattern required to assemble the overall knitting pattern as described in the following two sub-problems:

- Given a 2D weaving pattern design, segmentize the pattern to define the knotting unit, which has at least one (+) or (−) skein notation.
- Characterize the crease patterns to fold the whole paper strip into one segment so that all the half-cut line would mingle in one point for a single cut.

Based on this problem, the following three studies look at how this interwoven paper strip related to the assembly, form-finding, and structural issues in design.

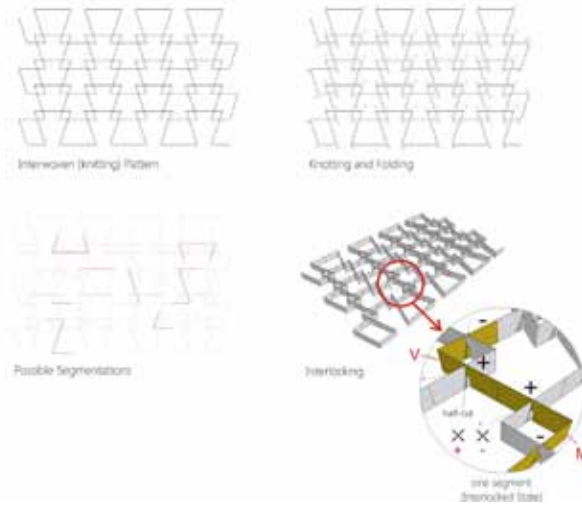


Figure 1. Interwoven surface as an interlocked, one continuous paper strip

3.1. ASSEMBLY: STRAIGHT SKELETON METHOD

In pursuing the half-cut pattern in the paper strip, we adopt the straight skeleton method and the one-dimensional flat-folding principle. In the straight-skeleton method, the skeleton is basically a folding crease that resulted from offsetting the edge of a particular graph to the inside until all the offset-edges collapse into a point (Aichholzer, 1995) and also as a reflection axis resulting from the bisection of two edges (Demaine, 2006). The trajectories between this point, bisector axis and all graph vertices, become the mountain-valley creases to fold the paper so that all original graph edges will meet in one straight skeleton line to be cut. In this case, the half-cuts are considered as the graph edge (Figure 2). When we position two identical half-cuts face to face, for instance, a neighbor of a notch is also a notch, and both of them are parallel. We may use only the offset method where the half-cut line between the half-cut will collapse right at the midpoint between the two and create just one M–V crease (Figure 4).

Otherwise, if the neighbor is different (i.e. the neighbor of notch is a parallel tab), we need a bisector method to first de-parallelize the two half-cuts from the diagonal axis between them, and then find the reflection axis between them, and create four M–V creases. With this method, we may be able to cut all random-distance, half-cut patterns in a single cut (Figure 3).

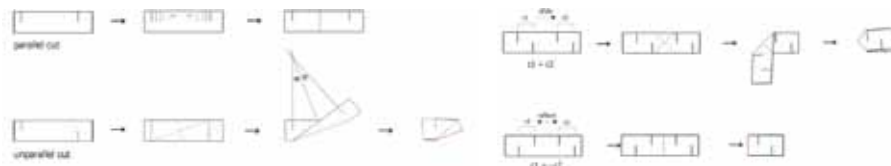


Figure 2. Half-cut distribution along the paper strip

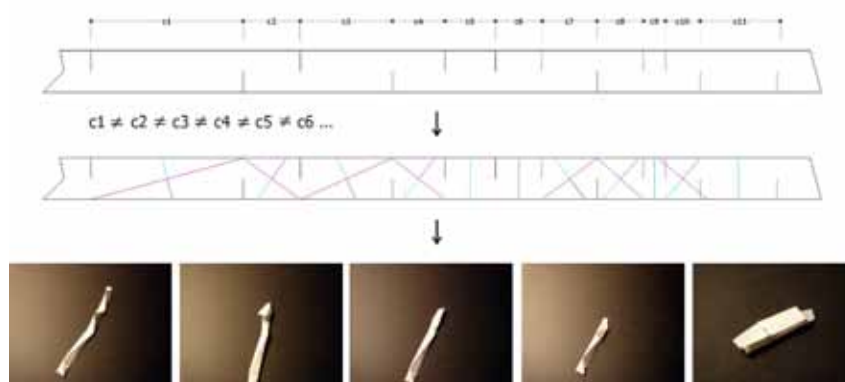


Figure 3. Random half-cut pattern in folded states

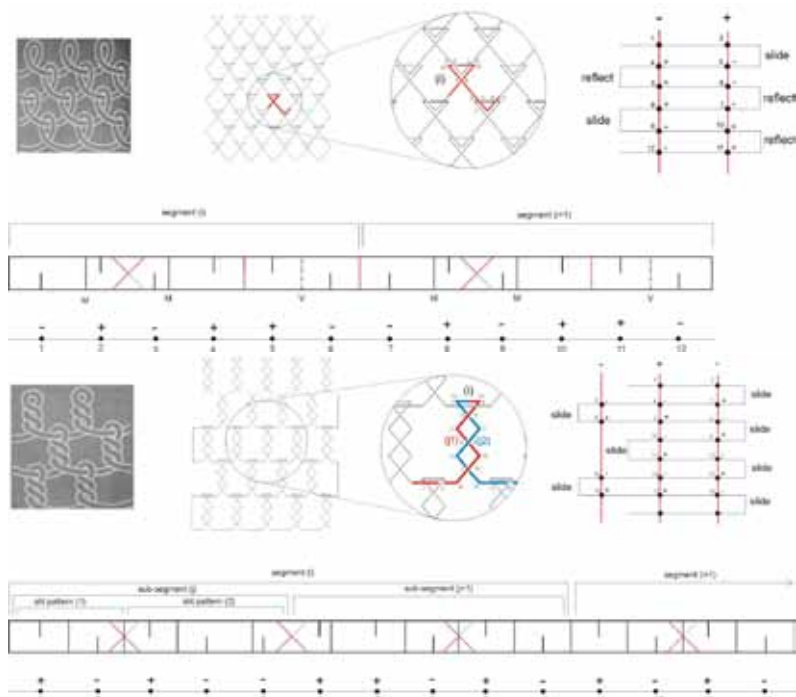


Figure 4. Converting an ancient looping knot into a paper strip pattern diagram.

3.2. FORM-FINDING: GLUING METHOD

Because a knot is considered homeomorphic to a circle in the algebraic topology, it can have numerous variants in its planar projection. A ten-crossing knot, for example, can have over 160 different projections on the knot table (Tait, 1860). Similarly, in folding algorithms, one Latin-cross polygon can be folded into 23 different convex polyhedral shapes by assigning different valley-mountain crease patterns and applying Alexandrov's theorem to join the edges and vertices (Demaine and O'Rourke, 2007). For this form-finding process, we exploit this ambiguity by combining these two types of representations. Alexandrov's gluing method works by looking at the possible paths that one vertex or edge might take to travel to other vertices and edges in the same polygon; these paths would then create mountain or valley crease patterns. Thus, in adapting Alexandrov's theorem in the paper strip activity, we essentially glue the half-cut vertices as a constant variable, and change the mountain-valley assignment as a parameter to generate different compositions. Figure 5 shows the basic rules for how to glue two vertices together as a knot's crossing point, as well as how to fold the paper strips to create convex or concave shapes within the mountain-valley assignment.

As a case study, we considered paper strips as the representation of the edges of three-dimensional objects (Figure 6). The generated designs in Figure 7 shows how we might have a different design by swapping the mountain-valley assignment and the crossing-point connection in a knot, each of which can potentially be transformed back to its three-dimensional shape to create a different architectural design.

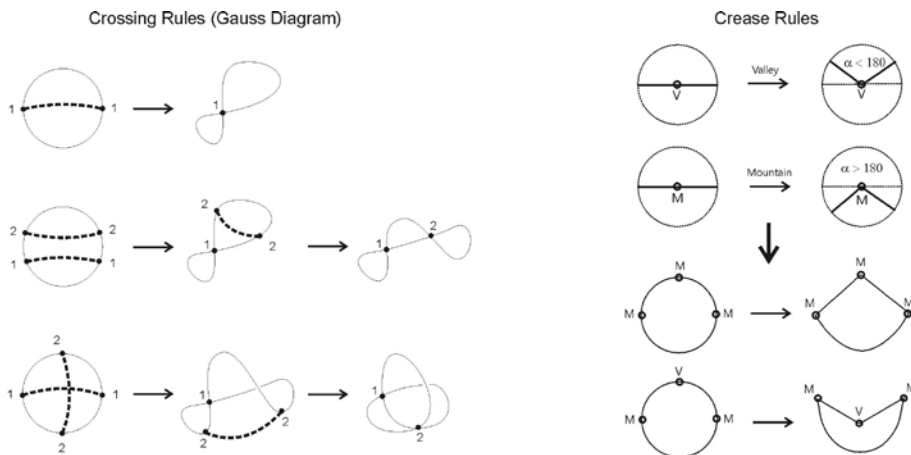


Figure 5. Knotting and Folding Rules

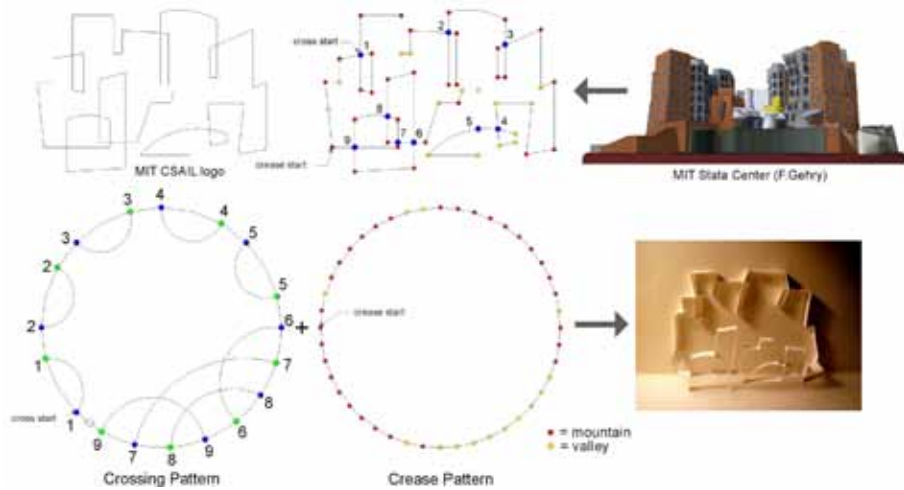


Figure 6. Knot as 2D Representation of Architectural Design

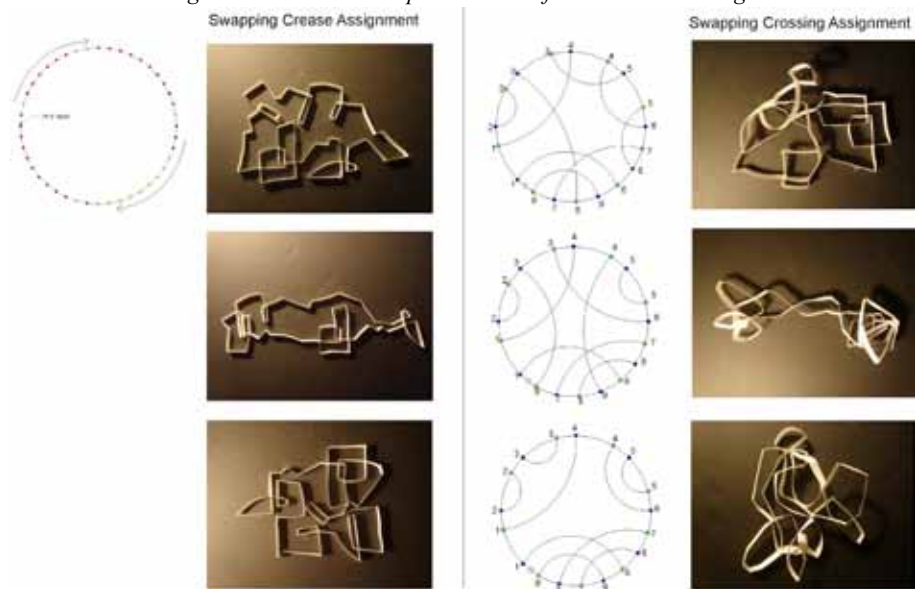


Figure 7. Modifying Crease and Knot Assignment to Generate Different Designs

3.3. STRUCTURE: LINKAGE RIGIDITY

The interwoven surface is rigid when a yarn segment performs a fixed-support structural joint by having an over-and-under configuration with other nonparallel yarns. As the number of crossings may be increased once a knot is pro-

jected in its planar projection, we need to investigate the looseness/tightness of a knot by reducing all the unknotted crossings into the knot's invariant; i.e., the real over-under configuration that tightens the knot. For this investigation, we use two approaches. First, we use three Reidemeister moves to undo the knot and find the *minimum* invariant of the real number of crossing point in 3D space (Reidemeister, 1926). Second, we use the Alexander-Conway Polynomial to assign a traverse direction to a knot (*oriented links*) and calculating the *linking number*—the number of invariants of a knot (K) resulting from the sum of the number of over (+1) and under (−1) at each traversed crossing point (P) [$\text{link}(K, L) = \sum P$, such that if $\sum P/2 = 0$ then $K = [\text{unknot}]$] (Alexander, 1928; Conway, 1970). This knot algorithm corresponds to the interlocked-chain problem in the folding algorithm. A tangled linkage is considered rigid if it is interlocked and cannot be separated, which would require at least a flexible three-chain with closed-quadrilateral linkage and a flexible four-chain with closed triangle linkage (Demaine et al, 2007).

Folding rigidity is also maintained by keeping the linkage consisting of exactly n joints and $2n - 3$ or more links to avoid the nontrivial motion of the joints and links (if the graph has fewer than $2n-3$ links, then it is never rigid) (Lamans, 1970) (Figure 8).

Thus, Alexander-Conway notation is useful to perform knot rigidity on the interwoven surface while Laman Theorems can evaluate the rigidity of the folded structure. In addition, the interweaving process also reveals that an area where the crossing points are very close to each other can be rather difficult to assemble even with a flexible paper strip. In this situation, it is necessary to loosen the knot by avoiding a crisscross over/under knot (e.g. + - + - + -) and instead, do an interval crossing (e.g. + + + - - - + + - -).

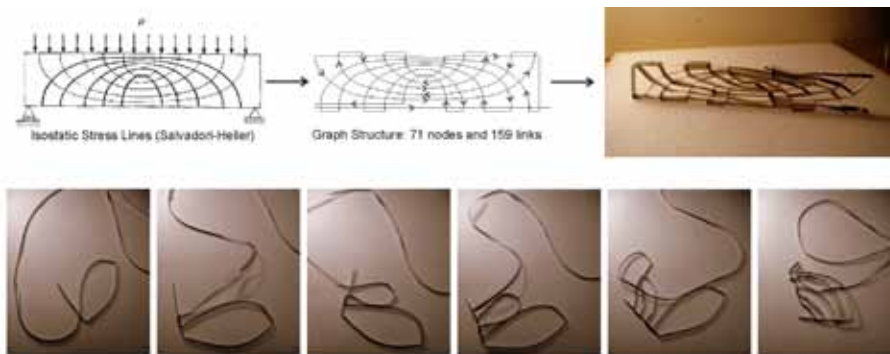


Figure 8. Stress lines as interwoven surface and assembly process



Figure 9. Load testing on the interwoven stress lines

4. Discussion

This research shows a novel way to generate a new kind of architecture based on traditional production technique. In particular, the experiments have demonstrated the role of one-dimensional paper strips in three domains:

- **Generative design.** The application of Alexandrov's Gluing Algorithm in Gauss's diagram shows an intrinsic feature of folding and knot theory to generate various computational designs by manipulating the crossing points and folding the creases physically. The use of paper strip in the form-finding experiments allows any type of one dimensional representation to be generated within this algorithm.
- **Fabrication.** Both folding and knotting can work seamlessly in the fabrication process to assemble interwoven surfaces with just one continuous straight paper strip. This process works well in both traditional and computational manner. The experiments were held with lesser digital computational devices yet the processes are combinatorial.
- **Structure.** The interwoven paper strips configuration exhibits some degree of rigidity that can support a uniform load distribution. This finding not only opens a new path for expressing ornamental structure in a more affordable way, but also allows an alternative view in assessing structural performance with knot and folding algorithm.

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ANALYSIS MODEL FOR INCREMENTAL PRECISION ALONG DESIGN STAGES

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Abstract. With current energy analysis tools, architects and engineers cannot rely on the results of energy analyses because they do not report their level of precision. In addition, current tools also do not deliver feedback in real time. Thus, this research addresses the challenge of obtaining feedback in real-time while gradually increasing precision along design stages. For this purpose, this study merges parametric modelling (PM) technologies and the performance-based design (PBD) paradigm into a general design model. The model is based on a parametric and an energy analysis model that share the parameters of a building. The modular architecture of the model involves four main function types: an input processor, optional analysis functions embedding different calculation methods, a decision-maker, and a report generator function. For every step of the design evolution, the decision-maker function generates a specific tree of analysis functions.

Keywords. Performance; decision-making; extensibility; knowledge-based design; design automation.

1. Introduction

The lack of interoperability between design and evaluation tools hinders the iterative process between design and energy analysis. To bridge this gap, the proposed analysis model addresses the question of how to include technical knowledge in different design stages. The main goals of the research are to obtain feedback in real-time for decision-making (Sanguinetti et al, 2010) and gradually increase the precision of such feedback while design is evolving. Obtaining this kind of feedback from technical domains requires the formalization of such expertise into a set of parameters, constraints, and functions.

This translation of knowledge is feasible since most design and engineering parametric software allows writing customized functions through their application programming interfaces (API). These capabilities allow users synchronize engineering with design knowledge instead of to perform analyses aside of the design process. This procedure allows users to visualize the effect of engineering knowledge directly in the parametric model and minimizes design further modifications. Furthermore, design and engineering knowledge embedded within parametric systems will drive the emergence of a new generation of design tools. The proposed model tackles such a challenge by joining both the performance-based design (PBD) paradigm and parametric modelling technologies (PM) using PBD as a guideline for an example of energy analysis and taking advantage from the parametric capabilities of existing CAD tools. While PBD characterizes how a product executes a given function under stress (Becker 2008), what a building must do instead of how it should be constructed (Kalay, 1999), PM allows design variation based on parameters that drive geometrical relationships (Aish et al, 2003).

The proposed model merges the PBD and PM approaches and synchronizes performance calculators with parametric models. Performance calculators simultaneously evaluate the parametric model of the building after every design variation, providing performance indicators (PI) that support decision-making. If more design resolution or details are added, the evaluation increases the precision of the results. Having different levels of precision from the same analysis model requires a variety of calculation methods selected based on provided inputs and desired outputs. The principle of *information hiding* (Parnas, 1972) is proposed to re-arrange the set of necessary functions embedding the calculation methods. For every evaluation, a new analysis program architecture is assembled. The implications and alternatives of this model will be discussed in the following sections.

2. Fundamental model for energy analysis

The activity-diagram shown in Figure 1 represents the process and different components that execute a regular energy analysis. The final outcome is an indicator of the energy required to maintain comfort temperature (Saguinetti et al 2010). The energy analysis model reads parameters from the parametric model, the weather, and materials. The number of aspects determines the number of required analysis functions containing different calculation methods. Although this particular example deals with energy consumption, the model can be adapted for a wider variety of performance aspects. As shown in the diagram, inputs from the building are combined with weather data, which together define the energy flow through the building (Hagentoft, 2003).

Building inputs such as orientation or shading areas are used for estimating heat gained through direct, diffuse, and reflected solar radiation (Szokolay, 2008). Finally, inputs from material properties are used for estimating energy transmitted through opaque and translucent surfaces. These kinds of models operate within any analysis tool with more or less variation. Outcomes are the result of an intricate flux of parameters among different analysis functions in which every function affects the precision of the results. Indeed, the prediction of results depends on how much knowledge we have, how much we want to invest to develop the model, and how much the prediction influences our design decisions (Paredis, 2007).

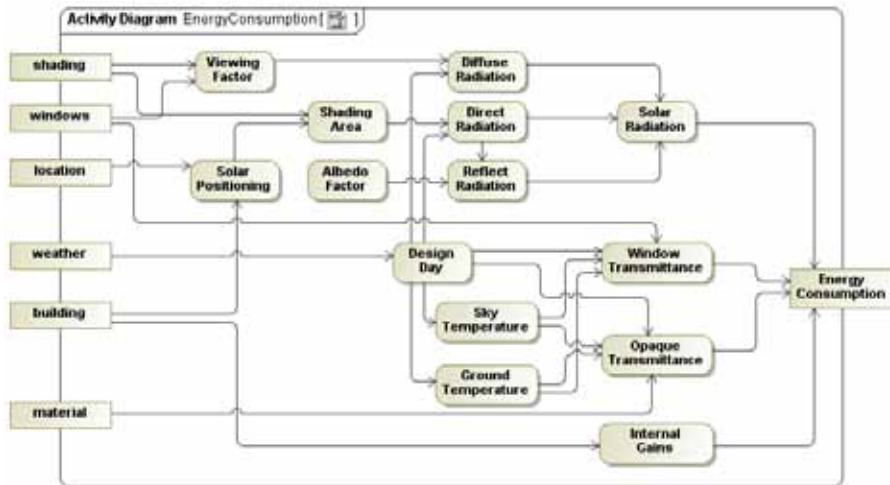


Figure 1. Diagram of the calculator for energy consumption, adapted from Sanguinetti et al

3. From the black-box to glass-box perspective

3.1. THE BLACK-BOX PERSPECTIVE

What happens within current energy analysis tools while the evaluation is executed? Few users can answer this question. Furthermore, how can we be confident about the results of an analysis of something we only partially understand? Most of the analytic tools operate under the black-box perspective. The tools process inputs and provide output hindering the chain of relationships, considerations, and calculation methods involved in the process. This lack of transparency is a key issue since the accuracy of results varies depending on calculation methods. For example, we can examine the process

that calculates the temperature of the sky (T_{sky}), a very important parameter involved in the calculation of the heat transferred by radiation through opaque and glazing surfaces. To obtain such a value in Celsius units, three different authors propose different methods.

- $T_{sky} = T_{air} [0.8 + ((T_{air} - 5) - 273)/250]^{1/4}$ (Bliss, 1961)
- $T_{sky} = T_{air} - \{ (1 - 0.261 \exp[-0.000777(273 - T_{air})^2]) T^{4/5.67 \times 10^{-8}} \}$ (Idso and Jackson, 1969)
- $T_{sky} = 1.2 T_{air} - 14$ (Hagentoft, 2001)

Those three methods use T_{air} , or current air temperature, as the main input. Nevertheless, later, to obtain T_{sky} they apply different methods. If we run the proposed calculation methods, we will obtain variations in the final result. Sorting these methods based on their precision is not an easy task for non-experts. Hagentoft proposes a simple way of estimating such a temperature by applying just a factor over T_{air} . However, determining the degree of precision of the other two methods seems to be more complex. The same dilemma occurs while we are calculating the other parameters involved in energy analyses. For diffuse solar radiation, we can apply a factor over direct solar radiation or perform the actual calculation. We can determine the viewing factor (how much sky we can see from a window to calculate loss because of radiation) by using a single reference point in the centre of the window or integrating several points to improve the accuracy. The definition of a reference design day varies depending on different records from weather data. We could select monthly, daily, or hourly records to determine maximum/minimum values or average values, generating a wide poll of possible design days for different purposes. Users cannot easily determine the precision of current evaluation tools since they hinder all these considerations.

3.2. THE GLASS-BOX PERSPECTIVE

Unlike the dominant black-box perspective, the glass-box perspective represents a different approach based on transparency. This perspective (Paredis, 2007) exposes the inner components of the model as a composition of interactions of black boxes, which makes the set of relationships between calculation methods involved in the process transparent and the assessment of the results by the users easier. Nevertheless, such approaches require some fundamental knowledge about physical phenomena from users if they want to assess what is going on within the glass box. In addition, calculation methods can be added or edited for specific purposes. Discrepancies from the calculation methods described above show that transparency is crucial because it can provide reliable feedback during the design process. From the glass box perspective users

should know if they are obtaining results on a monthly or hourly basis, the precision level of the method used to calculate any parameter, and the accumulated degree of uncertainty.

4. Features of the analysis model for incremental precision

4.1. FEEDBACK

The first target is to provide feedback to designers for decision-making. Design exploration is performed under the statement *what happens if*, which is not a naïve statement. On the contrary, it is an exploration based on implicit design knowledge, rules of thumb, previous experiences, good practices, or design guidelines. Along such an exploration, the analysis model should provide feedback from which users can visualize the outcomes or consequences of changes in the values of the parameters. This technique, which is based on exported parameters from the model through spreadsheets or simple text files, minimizes the complexity derived from the interoperability between formats since only parameters are shared between the parametric and the analysis model. Thus, having completed any modification in the parametric model, analysis model automatically updates and re-evaluates the parameters. Because most current parametric modelling software can share parameters, the approach of the proposed model can be applied for other kinds of analyses.

4.2. INCREMENTAL PRECISION

4.2.1. Shifting parameters

Along the design process, new parameters are constantly created and deleted. Parametric models typically have two kinds of parameters that are continuously evolving through the process: driving parameters in the top of the hierarchy (e.g., floor-to-floor height), and driven parameters (e.g., façade square feet). The analysis system should be robust enough to recognize the addition, edition, or deletion of those parameters.

4.2.2. Material parameters

The evolving material parameters involve material specification of the building components (e.g., U-values or solar heat gain coefficient SHGC for different window types). Although decisions regarding material specifications take place in late design stages, users can make some rough assumptions to perform the initial set of analyses. An analysis model for incremental preci-

sion must identify the replacement of default values for actual parameters and report the degree of precision of the analysis while these new parameters are added.

4.2.3. Weather data

Weather data information provide annual, monthly, daily, or even hourly average values. This variable source of information drastically influences the degree of precision of the performed analysis. Input variables such as ambient, ground, and sky temperatures, and direct, diffuse, and reflected solar radiation vary depending on the kind of information obtained from weather data. The analysis model should handle such a diversity of inputs.

4.2.4. Calculation methods

Analysis functions are another key component of the analysis model since results vary from rough estimations to more accurate values depending on the level of design definition (i.e., from monthly to hour-by-hour solar energy gains). Thus, analysis functions with similar signatures, embedding different calculation methods, could be assembled into a custom analysis model according to the complexity of the task, or the same function could provide different outcomes. If an input is null, the function could assign a default value or perform different calculations depending on the input types. Moreover, in the energy analysis field, we can identify two approaches that define calculation methods for physical phenomena: rough factors, derived from expert knowledge, and equations. For example, to estimate diffuse solar radiation, we can apply a factor on direct solar radiation or perform a more complex calculation obtaining different results from a lower to higher level of precision. In an adaptable analysis model, such considerations should be included in estimates of the degree of precision of any analysis.

4.3. EXTENSIBILITY

An adaptable analysis model grows by extending existing technology (Schaefer, 2010), integrating new knowledge, and re-using previous resources (Lee et al, 2005) to address new design challenges. Continuous improvement and infinite growth are fundamental features of an extensible analysis model. Continuous improvement maintains openness of the model by refining algorithms according to shifting conditions without affecting its functionality. Infinity growth implies that changes are implemented on a working platform based on the potential of the model to be modified by adding new functionalities or extending existing ones.

5. System modularity for incremental precision

The proposed model is based on a modular architecture by applying information-hiding principles (Parnas, 1972), that facilitate maintenance, allow parallel development, and increase flexibility since components can be added or replaced without affecting adjacent modules.

5.1. INFORMATION-HIDING PRINCIPLES

First, we must define module and function for the purpose of this paper. While a module is related to a responsibility task, a function is the actual implementation. A module has little knowledge about another module, usually it only exchanges inputs and outputs in the required format, and hides all the internal calculations. One or multiple modules, based on their affinity, can be embedded within a function, which can be constantly re-assembled, forming temporary structures responding to a given task without affecting the entire system (Parnas, 1972). Continuing with the example of the temperature of the sky and its three alternative calculation methods, we have two possible ways of implementing them: three alternative modules implemented in separated functions selected by external conditionals or one major function containing the three alternative modules. In the second case, internal conditionals decide what module should be used based on the input types.

5.2. ANALYSIS MODEL ARCHITECTURE

The proposed model (Figure 2) has four function types organized in a shifting hierarchical structure: input processor (IP), optional analysis functions (OAF), decision-maker (DM), and report generator (RG). IP handles inputs from the parametric model, material properties, and weather data. OAF perform actual evaluations. DM evaluates processed inputs, and based on this information, select different OAs from the options to perform the analysis. Finally, the RG collects results from the analysis functions and plots them for feedback.

5.2.1. *Input processor (IP)*

Inputs come from different sources such as dimensions from parametric models, weather data, or material properties. In addition, they are defined at different times along the design process. While parameters about massing studies of the building are shared in early design stages, parameters about material properties are defined in later stages. The task of the input processing functions is to properly evaluate and classify the incoming parameters to deliver them to the analysis functions. The input processing function must

read different formats from weather data in spreadsheets and parameters from text files to inputs provided by users. This function must also check if some parameters have or do not have information to assign default values or declare them null if necessary.

5.2.1. Optional analysis functions (OAF)

OAFs embed the calculation methods. Functions for design day, solar positioning, shaded windows area, albedo factor, and viewing factor must feed functions for sky and ground temperature, and diffuse, direct, and reflected solar radiation to determine the heat transmitted through walls and windows, the total solar radiation, and the internal gains that together determine the energy consumed to maintain thermal comfort. The OAFs can be implemented in two different ways: parallel functions with alternative methods to calculate the same value and one general function containing these multiple methods. In the first alternative, the DM selects what function must be used; in the second alternative, internal conditionals switch between different methods. In addition, OAFs should be as independent as possible, avoiding unnecessary cross linkage among modules to guarantee the required flexibility to re-arrange them along incremental steps.

5.2.1. Decision-maker (DM)

The DM controls the overall workflow. It reads pre-processed parameters from the inputs processing function and, based on such information, defines what function, or set of them, from the OAF is invoked to perform the analysis. The selected set of OAF will form a temporary tree depending on the required analysis and the desired degree of precision of the analysis.

5.2.1. Report generator (RG)

RG collects the outcomes and plot reports about current value of key parameters, the degree of accuracy of the overall analysis, and the amount of energy required for thermal comfort. Key parameters values can be represented through charts, but the graphic interface is a discussion for further steps. Although precision should increase while users add more resolution in terms of material specification, the uncertainty regarding material property inputs and the whole set of calculation methods involved in the analysis can affect the reliability of the results. The RG must take uncertainty into account for predictions, a coefficient (de Wit and Augenbroe, 2002) derived from inputs and calculation method. This coefficient is important since design decisions imply risk under uncertainty levels.

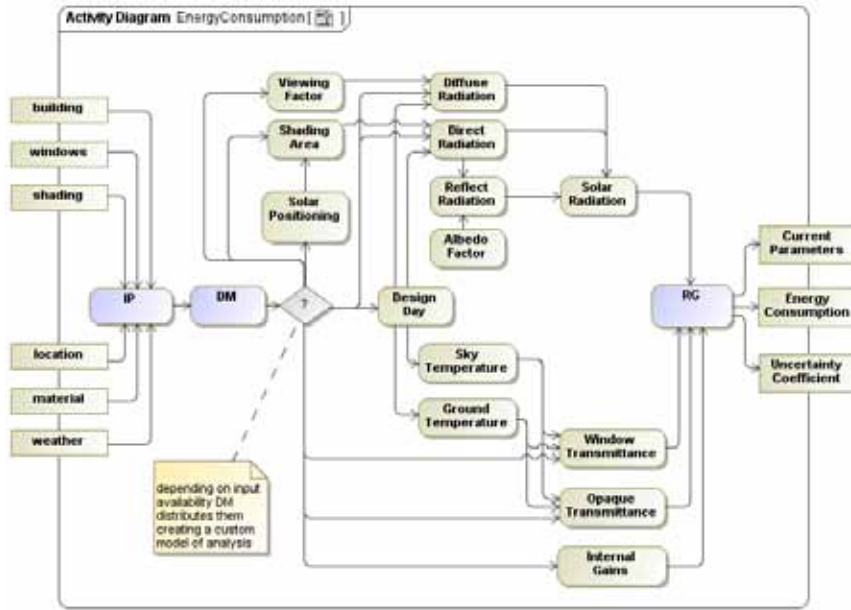


Figure 2. Activity diagram of the workflow of the proposed model

6. Discussion

The proposed model for incremental precision along sequential design stages provides support for decision-making throughout the design evolution. The technique in which the parametric and analysis models share parameters can provide feedback in real-time after every modification while the design increases the resolution of the material specifications. The model switches from the black-box to the glass-box perspective in terms of procedure, making the analysis process more transparent. The approach of this model reveals and clarifies the resolution of the analysis and the related levels of precision and uncertainty, but it demands that users monitor the analysis and the outcomes. Although this model adds transparency to the analysis, the model by itself does not achieve fully reliable results since the input and the calculation methods may introduce uncertainty and variations that affect the outcome. Discrepancies between different energy analysis handbooks show that no absolute methods exist, and users must have enough background regarding physical phenomena to make choices among alternative calculation methods. The consistency between degree of precision of the analysis and the importance of a design decision must be balanced in every design stage since differ-

ent decisions demand different information to be made. While some decisions in preliminary stages only require reference values, others in late stages could require more elaborated evaluations. Thus, the adequate degree of precision of the analysis is determined by the kind of decisions made by users. The precision of the predictions depends on one's level of knowledge, the extent of the investment in developing the model, and the degree of influence of the prediction on design decisions. Finally, knowledge from other domains can be translated to the analysis model by applying the same modular approach to extend the boundaries of the design environment.

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THE FLEXIBILITY OF LOGIC PROGRAMMING

Parametrically regenerating the Sagrada Família

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Abstract. Flexibility is a major attribute of parametric modelling, however designers find it hard to maintain flexibility throughout their projects. One cause may be the programming paradigm of the parametric model. Currently this is dataflow programming, which makes it easy to create and flex parameters, but difficult to modify relationships. This paper investigates the implications of changing the programming paradigm in a parametric model to logic programming. A qualitative account is given of using dataflow programming and logic programming to generate a portion of the Sagrada Família church. It finds logic programming adept at translating explicit models into parametric models, but lacking continuous flexibility. This research demonstrates there are different types of flexibility within the model and architects can privilege certain flexibility types by selecting the programming paradigm of the model.

Keywords. Logic programming; parametric modelling; end user programming; practice based research.

1. Introduction

In a parametric model, the geometry is a function of a finite set of parameters, with the collection of relationships between functions and parameters sometimes termed the schema. If the schema does not contain a parameter to modify the model in the desired way, the schema needs to be modified in a process Woodbury (2010) describes as “erase, edit, relate and repair.” The process of relating and repairing the schema can be time consuming, particularly if the consequence of these modifications needs to be traced through a

complex network of relationships. Mark Burry (1996) articulated one of the earliest instances of this problem in architectural practice, which occurred when he attempted to modify a schema of the Sagrada Família to generate paraboloids instead of conoids and concluded that there was “no solution other than to completely disassemble the model and restart at that critical decision.” Burry went on to suggest delaying the construction of the parametric model until the design problem is known, a practice that is common in contemporary architecture where parametric models are often not built until the design documentation stage. Constructing parametric models reveals “potential ranges of possibilities” and leads to further design exploration by design teams that, paradoxically, may not be accommodated in the schema of the model whose variability has suggested these new avenues. (Burry and Burry, 2006) The rigidity of parametric models to unanticipated design changes (a common occurrence in a cyclic design process) is a persistent problem that has not improved despite the now widespread use of parametric modelling in practice. Woodbury, Aish, and Kilian (2007) suggest that design changes can be anticipated through a series of ‘design patterns’ employed whilst constructing a parametric schema. Their work is significant for two reasons: firstly it suggests that parametric flexibility is related to the structure of the parametric schema; secondly it provides a model for improving parametric schema through appropriating software engineering principles from computer science.

In computer science, logic programming is one alternative to dataflow programming (the predominant software paradigm for parametric models). This paper investigates the affect on parametric models, in relation to their construction and modification, of changing the schema paradigm from a dataflow paradigm to a logic programming paradigm. The study gives a qualitative account of using the two paradigms to solve an actual design problem faced on Antonio Gaudí’s Sagrada Família church. The paper begins with the history of logic programming in architecture, followed by a description of the implementation method, and a discussion about using logic programming and dataflow programming to generate parametric schemas, before concluding with the findings of this study.

2. Schema paradigms and Logic Programming in architecture

2. 1. THE DATAFLOW PARAMETRIC SCHEMA



Figure 1. Left: A schema as a directed acyclic graph. The data from the two points flows to the line node informing its construction. Right: Geometry that results from schema on left.

The parametric schema is the collection of relationships within a parametric model. The schema can be represented as a directed acyclic graph, where the connection between nodes represents a relationship in the parametric model (Figure 1). This graph is a type of dataflow programming where the nodes represent operations and the edges describe the flow of data between operations. Modifying the input data, changes the data that flows through the graph, in turn modifying the output (In Figure 1, if the location of Point 1 is modified, the line is automatically redrawn). Being able to automatically redraw geometry by only modifying input data is one of the advantages of parametric modelling and can be thought of as *continuous* flexibility.

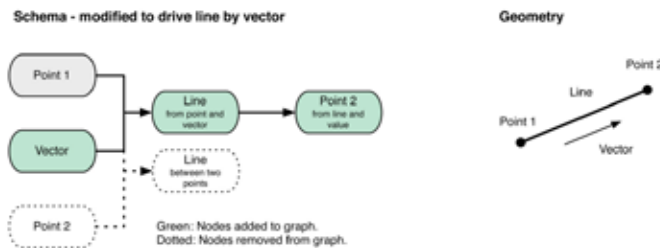


Figure 2. Left: Modification of schema in Figure 1 so that the line follows a vector. Note that Point 1 is all that remains of the schema in Figure 1, even though the geometry on the right has not changed radically.

Parametric models generated with dataflow programming can become difficult to modify if the model lacks an input to change the geometry in the desired way. When this occurs, the schema must be manually rebuilt to accommodate the new input in a process Woodbury (2010) describes as “erase, edit, relate and repair.” The model’s ability to undergo this process can be described as

discrete flexibility. In dataflow languages these processes can be problematic because relating and repairing relationships between nodes can change the flow of data with downstream consequences throughout the schema, even if the physical relationships between the geometry remains the same. Figure 2 shows adding a vector as an input to the schema in Figure 1 rearranges the relationships within the schema to the point where it would be easier to build the schema in Figure 2 from scratch than modify the schema in Figure 1. It is not uncommon for a complex production model to encounter these moments of discrete inflexibility, causing major time delays to the project while relationships are either reconstructed or the schema rebuilt from scratch (Burry and Burry, 2006).

2.2. LOGIC PROGRAMMING AND BACKGROUND WORK

One alternative to dataflow programming is logic programming. Using logic programming, the user can focus on describing relationships between objects and leave the logical inferences (in this case the way data flows in these relationships) for the computer to deduce. Logic programming has been the subject of much investigation within architecture, beginning with Swinson's 1982 paper *Logic Programming: a computing tool for the architect of the future*. Swinson utilised logic programming on four simple spatial planning problems and proposed this as an area for further investigation.

Following on from Swinson's work, there was a flurry of studies in the mid 80's through to the mid 90's. In 1984 Gonzales et al concluded, incorrectly, that computers and CAD will be based on logic programming in the future. The first examples of logic programming used to draw 2d parametric shapes came in 1985 from Brüderlin, and in 1986 from Helm and Marriott. A more comprehensive attempt to generate 3D parametric models was made by Woodbury (1990) using the ACEND language – not strictly a logic programming language, although it shares many similarities. In the same year Mitchell (1990) released the *Logic of Architecture*, which contains descriptions of architecture in first order logic, similar to Prolog. The closest project to our project in technical implementation is Aldefeld's (1988) use of forward-chaining to infer rules about constraints on parametric models. We use a similar method to infer rules about parametric schemata. A comprehensive review of logic programming in architecture between the mid 80's through to the mid 90's is documented in Fudos' PhD thesis (1995).

In the late 90's and 00's, research into logic programming in architecture dropped off dramatically. Despite this, there are still examples of logic programming experiments, such as Martin and Martin's *Ployformes* tool (1999) to draw complex polygons and Makris et al *MultiCAD* (2006), which com-

bin logic programming with a genetic algorithms.

Despite the optimism of Swinson, logic programming has not become the “computing tool for the architect of the future” (Swinson, 1982). It is interesting to note that for all of their proclamations about the future of architecture, none of the papers surveyed applied logic programming to an architecture project. This case study differs from prior research by testing logic programming in a highly contained geometrical design problem from the Sagrada Familia that exhibits the messy complexity, experienced in practice, of resolving multiple design constraints simultaneously. Unlike the previous research, which attempted to create the entire geometric model with logic programming, this research uniquely explores generating just the parametric schemata through logic programming and measures its success in relation to schema flexibility.

2.3. LOGIC PROGRAMMING APPLIED TO PARAMETRIC SCHEMA

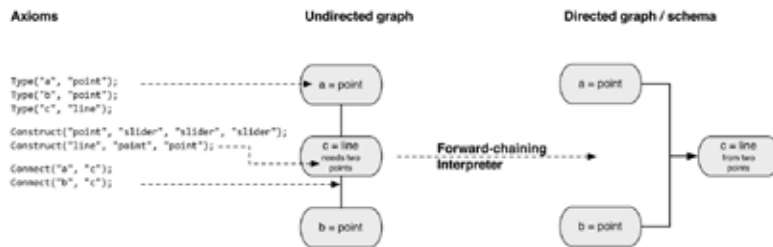


Figure 3. How a parametric schema is constructed with logic programming. Progression from axioms, into an undirected graph, which is then interpreted into a schema.

Defined by Sterling and Shapiro (1994), logic programming has two parts: a set of axioms “defining relationships between objects” and an interpreter that “deducts the consequences” of the axioms. These steps correspond to our logic programming process (Figure 3) where initially axioms about the schema are declared, then in an intermediate step the axioms are compiled into an undirected graph, and then finally the interpreter infers the flow of data through the schema. The interpreter is based on a forward-chaining reasoning method. In Figure 3, the interpreter can infer that Node A (a point) is the parent of Node C (a line) because the axioms declare that a line can be constructed from a point, and that a point cannot be constructed from a line. If the graph is over-constrained, the user is asked to resolve conflicts between the axioms. If the graph is under-constrained, a depth first search is applied to discover possible configurations for the user. Ideally the axioms will fully define the graph and the forward chaining interpreter will be able to infer the entire flow of data in the schema.

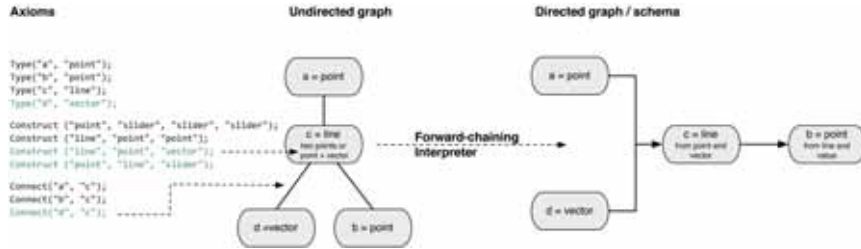


Figure 4. Modification of the axioms from Figure 3 so that a vector drives the schema. This is the same modification as was seen in Figure 2. The text in green is additional axioms from Figure 3, the interpreter then automatically rebuilds the schema from these axioms.

The benefit of this method is that the user only needs to define connections between nodes, while the interpreter can infer the parent-child orientation of these relationships, generating the flow of data. Therefore, rather than “erase, edit, relate and repair” the user only needs to erase and edit the axioms, with the relating and repairing automatically deduced by the logical interpreter. Figure 4 shows adding a vector as an input to the schema in Figure 3 can be achieved by adding four new axioms while the interpreter infers the new data-flow (contrast this to the example in Figure 2, where, one the same problem, rebuilding the dataflow schema was easier than modifying it). This example depicts how the forward-chaining interpreter can carry out the stages of relating and repairing during a discrete modification of the schema, although this example also exposes how an additional layer of abstraction could make it difficult for the user to understand why interpreter has constructed particular relationships.

3. Application to the Sagrada Família

This section compares dataflow programming and logic programming as a method to solve a real constraint problem in the geometry for the ‘Fronton’ (gable) of the Sagrada Família.

3.1. THE PROBLEM FACED ON THE SAGRADA FAMÍLIA

The Sagrada Família by Antoni Gaudí’s has been under construction in Barcelona, Spain since 1882. Design and construction has recently commenced on the tower of Jesus; the central tower above the crossing. Forming the base of this tower are the ‘Frontons’ which are a matching set of 17 metre high arches placed above three windows on opposite sides of the tower. The Frontons were designed parametrically, however during the design process they were converted into explicit geometry and over subsequent revisions the original

parametric properties became lost. In 2010, during the preparation of the construction documentation for the Frontons, it was decided the original parametric rules needed to be reapplied to the distorted geometry by converting it back into a parametric model. An example of the distortions is given in Figure 5.

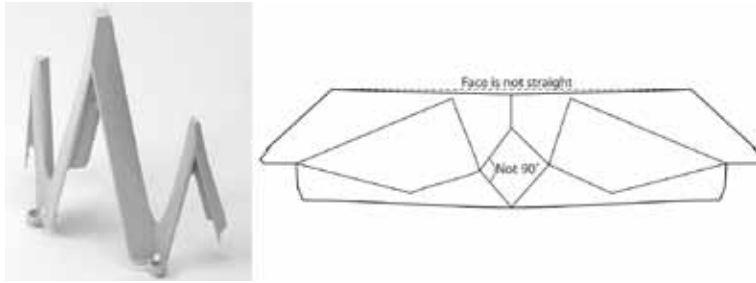


Figure 5. Left: Final version of the Fronton produced by dataflow programming. Right: Plan view of Frontons illustrating two problems with the original model, faces that were not orthogonal and angles that were not correct – every face had one of these errors.

3.2. USING A DATAFLOW SCHEMA

The conversion of the Frontons from an explicit model to a parametric model was initially undertaken using a dataflow parametric model. The process of generating the model occurred over a period of two weeks and took 32 hours. The final dataflow model was driven from 35 numeric parameters, which flowed through approximately 3000 connections to 1050 operations generating the revised geometry of the Frontons. The architects asked for two modifications, but fortunately the schema was developed with parameters anticipating these changes and the modifications occurred without rebuilding the schema.

3.3. USING A LOGIC PROGRAMMING SCHEMA

The same problem of converting the explicit model of the Frontons to a parametric model was solved with logic programming. Approximately 600 axioms were required to generate the schema. Most axioms could be automatically generated by a program that identified the geometric relationships already present in the explicit model (this can not be done on a graph based schema because they require not only the relationship, but the orientation of the relationship as well). The remaining 100 axioms were generated manually in a process that took 5 hours, making it significantly faster than dataflow programming. The two modifications could be accommodated by adding new axioms and this in turn allowed the forward-chaining algorithm to infer the

modified schema.

4. Comparison and discussion

4.1. RELATIVE SPEED

It was approximately 5 times faster to build the schema with logic programming compared to dataflow programming. The increase in speed came from logic programming being able to generate large parts of the axioms automatically from the already existing, explicit, geometry of the Frontons. This speed advantage seems highly problem dependent and any problem that does not involve converting explicit geometry into a parametric model is unlikely generate such a speed difference.

4.2. LEGIBILITY

As the complexity of the schemas increased, both methods became illegible. In the dataflow language the connections were like spaghetti, making it difficult to track what rules had been applied; on three occasions rules were not applied because they seemed to be already present, a fact only uncovered by project architects measuring the model. Logic programming was equally difficult to read because it referred to geometry by name and it was difficult to assign meaningful names to the 111 points and 96 surfaces. This was slightly mitigated by grouping axioms together, so even if the axioms were illegible, the user could understand a group's function. The extra layer of abstraction generated by using logic programming was not an issue in this case because the problem was so complex the only way to understand the system was through the output, in this case the geometry. Legibility is still a largely unexplored aspect of parametric modelling. It has implications for the use (and reuse) of parametric models in a team environment because editing the model requires comprehending it first. Neither dataflow programming nor logic programming addresses this issue, but modular programming or unit testing may offer fruitful areas of enquiry.

4.3. FLEXIBILITY

Flexibility is often described on a spectrum of more flexible and less flexible. Indeed the premise of this research was to discover a *more flexible* parametric modelling technique. However, *more flexible* is an insufficient description of the differences between logic programming and dataflow programming. Flexibility is not a spectrum, it is a combination of modelling attributes whose measurements is context dependent.

In the context of a real constraint problem in the geometry for the Fronton of the Sagrada Família: logic programming was the more flexible way to generate the schema from explicit geometry; both methods were equally flexible when making the required changes, although changes took significantly longer to propagate in logic programming; and both methods were equally illegible when identifying where to make the changes. However, this can not be extrapolated to all modelling situations because the results are highly dependent upon circumstance – such as there being pre-existing explicit geometry and the problem being of a high level of complexity. What can be extrapolated is the characteristic flexibility of the programming paradigm in each of these aspects – logic programming is likely to be more flexible than graph based modelling when converting explicit models to parametric models, and likewise, dataflow programming is likely to be more flexible when propagating parameter changes through the model. Since a parametric model cannot be easily switched from one programming paradigm to the other, the initial decision regarding what programming paradigm to generate the parametric model in, is critical. This is a decision can help make the model more or less flexible in particular aspects of flexibility. Further research is needed to help guide designers in making this decision.

4.4 HAVE WE SEEN THIS BEFORE?

In many ways, the current situation with inflexible parametric models mirrors the 1960's 'software crisis' where the major hindrance to the application of computation became the software developer's ability to write code for these complex problems. In a similar way, the current limitation on parametric modelling is the designer's ability to generate a flexible parametric model, particularly when faced with the complexity of pioneering projects like the Sagrada Família. There was no 'silver bullet' to the software crisis, instead new programming paradigms, new ways of structuring code, new code libraries, new environments for generating code and new ways of managing code development, helped pull programming out of its crisis (Brooks, 2010). This research has shown that the programming paradigm of the parametric model is one way to influence model flexibility, but there is still much more to learn from how software engineers structure code.

5. Conclusion

Logic programming is not a 'silver bullet' for parametric flexibility. Instead, this paper has shown that flexibility manifests in different forms within the parametric model, and that the programming paradigm of the model has some

influence over these types of flexibility. By selecting the programming paradigm the designer can privilege certain types of flexibility, although how to make this decision deserves to be further explored. In this study, our novel application of logic programming to the generation of parametric schema, facilitated the translation of an explicit model into a parametric model while hindering the continuous flexibility of the model, when compared to a similar model created with dataflow programming. This paper has demonstrated that the programming paradigm has a significant impact on how long a parametric model takes to generate, as well as types of flexibility present.

Acknowledgements

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PARAMETRIC MODELLING AND DESIGN PROCESSES

Exploring synthesis and evaluation using a Function-Behaviour-Structure perspective

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Abstract. In an attempt to extend our understanding of the design process in the context of computational parametric design tools, this paper explores the relationship between and interaction of synthesis and evaluation. In establishing the importance of their coupling in parametric design the paper then explores its consequence on the design process relative to existing models of designing. A tension between designing as planning, search and exploration in parametric design is highlighted together with a conceptual framework, which draws from a situated Function-Behaviour-Structure model of design. The purpose of the framework is to facilitate these different modes of designing and is targeted at the use of parametric tools.

Keywords. Design processes; parametric design; evaluation; synthesis, design models.

1. Introduction

Designing in the context of computational parametric tools is a nascent area of design research. The complexity and power of parametric design software, such as Digital Project, Generative Components and Grasshopper, and their impact on the design process remains relatively unexplored. Its complexity lie in the need to describe the (often as yet unformulated) design artefact during the early design phases by assigning parameters, identifying their relationships to each other, and defining the criteria by which the design will be evaluated. The designer must consider any potential design solution not as a static

artifact, but rather as a flexible system that has varying levels of adaptability, together with the system's capacity to generate divergent alternatives and evaluate them. The power of parametric design software thereby lies in its generative and performative capacities.

However the ability to generate and evaluate alternative design solutions reveals a tension in designing with parametric tools between 'designing as planning', 'designing as search' and 'designing as exploration'. On the one hand, the capacity to generate solutions introduces the requirement to *plan* and to *search* for appropriate solutions whilst, on the other hand, the state space of possible designs to be searched is not necessarily available at the outset of the design process and designing as *exploration* will therefore involve not specifying or even being able to specify all that needs to be known to produce a design (Gero 1998).

Here designing involves finding the behaviours, the possible structures and /or the means of achieving them – yet these are only poorly known at the outset (Logan and Smithers, 1993; Gero, 1994). Consequently, the use of parametric tools in the schematic phase of architectural building design is still quite limited, and in the conceptual design phase even more so. In extending our understanding of the design process in the context of computational parametric design tools, this paper shall first presents case studies of parametric designing, before then considering these examples relative to the interaction between synthesis and evaluation. In establishing the importance of their coupling in parametric design the paper then explores its consequence on the design process relative to existing models of designing. A tension between designing as planning, search and as exploration in parametric design is highlighted together with a conceptual framework, which draws from a situated Function-Behaviour-Structure model of design, and aims to facilitate these modes of designing in a method targeted at the use of parametric tools. The paper closes with a discussion of future work.

2. Parametric methods and processes in architectural design

In the use of parametric design tools, the schematic phase is important, with architects and engineers using planning, search and exploration methods to create alternative architectural solutions. Potential design alternatives are generated and evaluated in order to obtain the most promising design. A parametric approach to designing includes using the computer not only for visualisation, analysis and evaluation, but also for the rapid generation of computable design representations describing alternatives. The following case studies outline some example design workflows that, as we shall argue, emphasise the interplay between synthesis and evaluation.

2.1 EXAMPLE DESIGN CASES

The introduction of analysis software into the design workflow has widened the scope for understanding and assessing design aspects visually during the design process. This capability allows greater confidence in design development by increasing levels of certainty that a design will perform as intended by the designer.

2.1.1 *Constructability*

The evaluation of constructability is an emerging approach to the use of computation and is becoming an increasingly critical component of architects using advanced technologies during the design process. Gehry Partner's computational methodologies, specifically the concept of surface rationalisation (Shelden 2002), is one such example. The manufacturing limits can be encoded as algorithms and the search for a rational solution becomes automated. Subsequently, in cases of, e.g., façade curvature, the curvature of the skin can be assessed for constructability and iteratively rationalised as required. Hence, a direct connection between the manufacturers' evaluation criteria is formed with the digital model providing a means for the designer to interact and iteratively develop the forms until they comply.

2.1.2 *Structure*

Sasaki (2008) describes the process of shape evolution on a series of roof structures using the sensitivity analysis method; an evolutionary process involving the adjustment of height values of a given roof mesh with continual structural assessment to generate a minimal stress solution. The form enters into a continual negotiation between the 'ideal' architectural shape and the structural requirements to minimise and rationalise the roof. Critically, during the schematic design phase, both architectural and structural evaluation criterion are present.

3. Coupling synthesis and evaluation

The above examples reveal an interesting but core aspect of not only parametric design but design in general: the coupling of synthesis and evaluation and the benefits of coupling the evaluation criteria into the synthesis stage. For architectural design, the importance of evaluation criteria in the setup of the parametric model becomes more complex. The logical ordered processes of well documented and often cited design methods break down in favour of a more flexible model more akin to descriptions of designing based on the co-evolution of problem and solution spaces (Maher et al 1996).

What distinguishes designing in the context of parametric tools is the reliance on the interaction between the synthesis and evaluation. That is, the representation (and re-representation) of the design solution and the continual development of sets of evaluation criteria. The examples presented in §2 illustrates the early and recurrent coupling of the design representation and evaluation criteria and how this diffuses distinctions between typical stages of the design process. To explore this aspect further the following section shall discuss some well known models of designing.

4. Models of designing

The historical approach of understanding design processes have spawned from formal methods of logic, mathematics and operations research into models of designing (Alexander, 1964; Mitchell, 1977). The introduction of artificial intelligence concepts are an attempt to expand those approaches (Coyne et al, 1990), and now tools from cognitive science are providing more insight into aspects of human designing (Lawson, 1990; Cross, Christiaans and Dorst, 1996). Gero defines designing as a sequence of acts which may be described through processes (Gero 1998). The act of designing has therefore been modelled at various levels of abstraction by researchers in the design methods community. This section explores two well known models and discusses them in relation to parametric design.

4.1 ASIMOV'S MODEL

Perhaps the earliest of the widely accepted models of designing is described by Asimov (1962) who divided all designing processes into three classes: Analysis, Synthesis and Evaluation. Asimov and others ordered these as processes as shown in Figure 1.

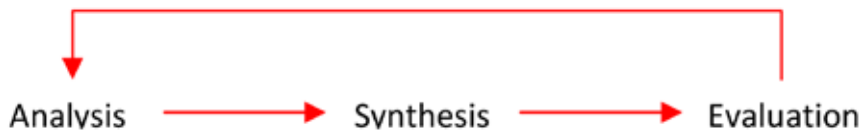


Figure 1. The analysis, synthesis, evaluation model, source Gero (1998).

This model has been used to explain what it is that designers do when they are designing. The processes involved in this view of designing use a terminology which is no longer widely accepted. The term “analysis” has been replaced by “formulation” or similar terms and “analysis” is now used to refer to a precursor of evaluation.

4.2 FUNCTION-BEHAVIOUR-STRUCTURE MODEL

There have been numerous models developed related to Asimov's original description of designing, as well as a number of formal theories and methods. However one model that distinguishes itself is the function-behaviour-structure (F-B-S) model as it abstracts the processes of designing even further (Gero, 1990). The schema represents design knowledge in the form of the three abstract notions of function (F), behaviour (B) and structure (S) of a design object. These three notions are defined as follows:

- The function (F) of a design object is defined as its teleology.
- The behaviour (B) of a design object is defined as the attributes that are derived or expected from its structure.
- The structure (S) of a design object is defined as its elements and their relationships.

The F-B-S model, shown in Figure 2, provides a framework for eight processes, namely:

1. formulation: $F \rightarrow Be$	5. documentation: $S \rightarrow D$
2. synthesis: $Be \rightarrow S$ via Bs	6. reformulation - 1: $S \rightarrow S'$
3. analysis: $S \rightarrow Bs$	7. reformulation - 2: $S \rightarrow Be$
4. evaluation: $Bs \leftrightarrow Be$	8. reformulation - 3: $S \rightarrow F$ via Be

Processes 1 through 5 match with those that appear in earlier models such as the Asimov model, where behaviour is bifurcated into expected behaviour, Be , and behaviour derived from structure or actual behaviour, Bs . The class of processes represented by processes 6 through 8, described in detail in §5.1, although recognised, have not been well articulated in many models, partly because they have not been well understood (Gero 1998).

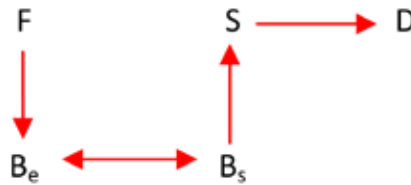


Figure 2. F-B-S model, source Gero (1998).

4.3 MODELS OF DESIGNING AND PARAMETRIC DESIGN

Whilst these approaches were promising, claiming the ability to handle complex design scenarios through systems logic and rationality, the failures

of these methods are well documented due to their inability to successfully operate when it comes to the realities of designing. To highlight the constraints of these models relative to parametric design tools it is useful to distinguish three modes of designing: designing as planning, designing as search, and designing as exploration. Whilst it is understood that there are differing definitions for modes of designing, this particular classification demonstrates succinctly a range of design modes which associate well with parametric design processes.

4.3.1 Designing as Planning

With its conceptions rooted in artificial intelligence, planning is understood as the determination of a sequence of actions required to progress from a starting state to a goal state. Planning has been used to model design (Gero 1987). Implicit in its framework is a bounded state space which limits the consideration as a model for designing to detail or routine designing. Parametric design software has been idealised as the solution to rationalising design, however the time invested in the planning and construction of these systems cannot keep up with the changing pace of the design workflow (Burry 2003). Parametric systems require an investment into the planning and construction of the design logic or rules, hence there is considerable development of the ‘formulation’ stage of the design process which results in the ability to generate solutions.

4.3.2 Designing as Search

Search as a computational process for designing capitalises on a history of artificial intelligence techniques (Coyne et al, 1990). The limiting factor of search for design is in the basic and often implicit assumption that the state space of all possible designs is defined *a priori* and is bounded. In the use of parametric design tools, the searchable state space can be mapped onto the parametric system setup and the criteria used to evaluate the state map onto behaviours, hence corresponding to the F-B-S model.

The designing process focuses on means of traversing this state space to locate either an appropriate or the most appropriate solution. The advantages of modelling designing as search include the ability to search spaces described symbolically rather than only numerically, referencing a core principle of parametric design, i.e. the ability to abstract design into a symbolic representation of nodes and relationships allowing it to be instantiated into new situations (Woodbury, 2010). In this model of designing, there is a focus on both the search methods and the relevant criteria to be used. However, the

assumption that the space is defined prior to searching relegates this model to detail or routine designing (Gero 1998).

4.3.3 Designing as Exploration

Designing as exploration recognises that necessary information required to construct a state space of possible designs is not always available at the outset of the design process. In this model, designing involves an exploration of behaviours, possible structures and/or the means of achieving them (Logan and Smithers, 1993; Gero, 1994).

Designing as exploration provides another dimension in the use of parametric design tools that relates to the idea of non-routine designing: not specifying or even being able to specify at the outset all that needs to be known to produce a design. For example, parametric designers often do not know at the outset the limitations of a system until it is constructed and tested. Designing has long been recognised as belonging to the class of problems called “wicked” problems (Rittel and Webber, 1973), exploration is an attempt to deal with this issue and is an essential part of the process when designing with parametric tools.

4.4 INADEQUACIES OF DESIGN MODELS

As early as 1970, the difficulties of systematic procedures, defined by models of designing, to account for the design situation was acknowledged. Jones claims that “losing control of the design situation once one is committed to a systematic procedure, which seems to fit the problem less and less as designing proceeds” (Jones 1970). Researchers have since highlighted the inability of these models to address a range of phenomenon significant to the design process, including among others the concepts of situatedness and constructive memory. Situatedness (Clancey, 1997), in contrast to the static world inherent in a large extent of the artificial intelligence view of knowledge, has its major concern of locating everything in a context. Hence decisions that are taken are a function of both the situation and the way the situation is constructed or interpreted. The notion of constructive memory fits well with the concept of situatedness, with the understanding that memory is constructed in response to any demand on that experience (Rosenfield, 1988). Thus the memory of an experience may be a function of the situation in which the question, which provokes the construction of that memory, is asked (Gero, 1998).

5. Toward a framework for designing with parametric tools

The ability of parametric tools to generate alternatives and evaluate their suit-

ability can be characterised by the three forms of designing described in §4.3 i.e., by planning, search, exploration or any combination of the three. Understanding the design workflow as a constant flux between formulation, synthesis, analysis and evaluation represents the typical workflow of parametric designing.

What this paper emphasises is that these typical processes that underpin parametric design place greater attention on the analysis method and how it is defined relative to expected behaviour. Setting up a parametric rig forces not only the synthesis of expected behaviour into structure, but also defines how any potential design solution will be evaluated, i.e., how its actual behaviour will perform. These case studies demonstrate that the coupling of synthesis and evaluation tend to limit the design workflow to *Designing as Search* and hence restrict the effectiveness of parametric tools, such as Generative Components and Grasshopper in helping designers solve non-routine design problems. From this perspective, Gero's *situated* F-B-S model has much to offer in developing an understanding of and augmenting the processes of parametric designing.

5.1 THE SITUATED F-B-S MODEL AND PARAMETRIC DESIGNING

The F-B-S model provides a framework which remains unchanged by the introduction of situatedness into designing. Gero illustrates that the most obvious and most interesting place to locate situatedness is in the reformulation phase. What can be inferred here is the significance of evaluation in any reformulation process, both in terms of the criteria utilised and the outcome of evaluation. Of the eight design processes listed earlier in §4.2 three were concerned with reformulation (labelled processes 6, 7 and 8) and have direct implications in parametric designing.

The first of these, reformulation – 1, occurs when the structure state space is modified. Here the role of the situation is to provide opportunities to source new structure variables, Figure 6a. In the use of parametric design tools, a typical process resulting from evaluation is the use of induction. However, this will be dependent on both the perception of what can be the source in induction and/or whether the source is defined by any initial evaluation criteria.

Design process 7, reformulation – 2, figure 6b, involves redefining what expected behaviours are proposed as a result of evaluation since they bring with them their own ancillary behaviours. Alternately, new behaviours may be derived from evaluation methods. Existing behaviours may be dropped if they are shown to play no discriminatory role.

Design process 8, reformulation – 3, involves redefining what the functions are to be as a consequence of evaluation, Figure 6c. Redefining functions

for an artefact has the potential to change the expected behaviours as well as the resulting structure. New functions are derived from the situation.

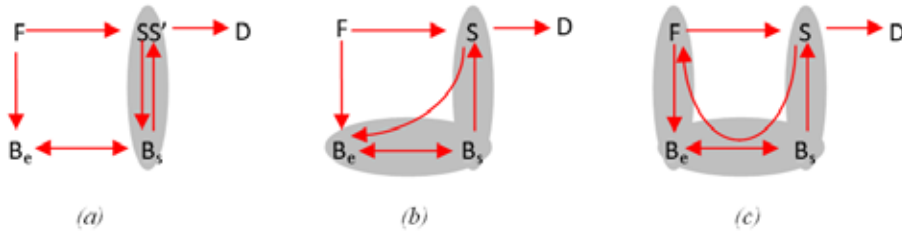


Figure 3. (a) Transforming S to S' is based on the situation (b) Transforming the expected behaviours is a function of the situation which exists in terms of the structure synthesised up to this point and the discriminatory capacities of the existing behaviours, (c) Redefining the functions or purposes of the artefact is dependent on the situation.

The situated F–B–S model provides a conceptual framework for parametric designing which has the capacity to explain as well as describe. That is, the model can be used to develop methods which support parametric designers whilst they are working at both the early and later stages of designing by providing a means by which to direct activities and on which to build and refine evaluation techniques.

6. Discussion

This paper claims that in designing with computational parametric tools and establishing the parametric system, or ‘rig’, during the early fuzzy front end that the tensions between ‘designing as planning’, ‘designing as search’ and ‘designing as exploration’ is produced due to the need to assign not only parameters and relationships but also the need to define some basis for evaluation during the formulation phase. It is furthermore essential that evaluation criteria are understood and can be developed throughout each phase of designing, i.e., during reformulation in conjunction with formulation, synthesis, and analysis, relative to the design’s function, behaviour and structure.

In developing the conceptual framework in future stages of this research, three further questions are raised: (1) what evaluation techniques are available to designers, (2) how can evaluation criteria be imputed throughout the development of the parametric system, and (3) what sets of quantitative and qualitative evaluation criteria can be identified and amalgamated to support the three types of reformulation processes identified? These topics will be considered in further studies with the overall goal being, if evaluation criteria can be understood computationally as an integral part of the reformulation

processes of design, there is an opportunity to achieve some of the original aims of computational design systems, precisely the ability to generate innovative and advanced non-routine design solutions.

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COMPUTATIONAL LANDSCAPE DESIGN WITH THE SEED SCATTERING SYSTEM

A case study in the Sony forest project

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Abstract. This paper proposes a computational landscape design method, called *the seeds scattering system* (SS system), which enables us to manage various environmental parameters in design processes, to create the ‘natural forest’ in urban environments. First, this paper discusses the drawbacks of the conventional methods for landscape design. Second, the paper outlines the components of the SS system together with the design process of the SONY forest project in Tokyo, and shows its advantages, including broad applicability to conceptual design, and capability of environmental simulations and spatial optimizations. Last, the paper summarizes the effectiveness of the SS system. By managing fundamental rules behind geometries in forest growth processes, the SS system showed us capability for constructing interactive relationships between design and their surrounding environments to produce design inherent in its site.

Keywords. Computational landscape design, parameter, tool customization, optimization, sensor network system.

1. Introduction

The objective of this paper is to propose a computational landscape method, which we (AnS Studio) developed in the SONY forest project in collaboration with Kazuhiko Yamanashi design team (Nikken Sekkei, an architectural design office). Our method is inspired by algorithmic design and algorithmic botany.

According to Kostas (2006), algorithmic design involves the designation of software programs that generate space and form according to rules

inherent in architectures. On the other hand, algorithmic botany means the studies on biological modelling and visualization carried by a research group in the department of computer science at the University of Calgary. The group applies notions and methods of computer science to gain a better understanding of the emergence of forms and patterns in nature. What is common to the algorithmic design and the algorithmic botany is that they try to understand and handle fundamental rules behind forms. By applying these methods to landscape design, we developed a new landscape design method.

In the following Section 2, we discuss the drawbacks of the conventional methods of landscape design. To overcome these drawbacks, we propose the SS system. In Section 3, we describe a background of the SONY forest project. In Section 4, we present the functions of the SS system together with the design process of the project. In the last section, we summarize the effectiveness of the SS system.

2. The project background

In design processes, architectural designers mainly deal with buildings and artefacts; in contrast landscape designers mainly deal with plants and natural objects. Because every plant has its own suitable environments, a critical part in landscape design processes is to survey environmental conditions of project sites, and to select plants adaptable to those conditions. It is also critical to take plant growth into account in landscape design processes. For instance, in the SONY forest project, the average tree height is about five to six meters and that of the tree width is about two to three meters at the beginning; however, in 30 years, both tree height and tree width will be doubled. Therefore, it is very important to consider future environmental conditions for every species of plants in landscape design processes.

As noted above, environmental conditions and plant growth are key elements in landscape design processes. In addition, appearances of plants, such as plant geometries, colours, textures, blooming and foliage seasons, are also basic factors to be considered in landscape design. From a biological standpoint, all these factors are intricately interacting with each other. In conventional landscape design processes, landscape designers handle these factors separately in the following three independent design steps.

- **Design step 1:** Survey environmental conditions and select plants.
- **Design step 2:** Layout those plants by appearances of plants.
- **Design step 3:** Plan a program for managing plants from the present to the future.

Let us next discuss the current state of environmental researches including

natural and urban environmental researches. In the past, tasks of environmental survey were time-consuming. They spent a lot of time in obtaining environmental data because sensor technologies were not so well developed as those of today. Even if they could get data, it took much time to analyze those data because current high-performance computers were not available at that time. Nowadays, owing to advanced technologies, we can easily obtain a huge amount of precise environment data, and analyze those data quickly. In addition, progress in computational fluid dynamics simulation systems with numerical methods and algorithms contributes to advancing in environmental researches.

At the same time, growing awareness of environments also accelerates developments in environmental researches. For example, in Japan, architects are required to assess the environments surrounding of a building when they propose large-scale building projects. As a result, various environmental researches and simulations are carried out before building construction. However, the resulting data are rarely used in design processes, and they are used only for checking legal obligation or persuading clients.

To solve the above mentioned problems, we propose the seed scattering system, which is characterized by the following two distinct features.

- **Feature 1:** The system can manage environmental conditions, plants growth and appearances of plants in an interactive manner in design processes.
- **Feature 2:** The system can manage a huge amount of environmental data.

3. The SONY forest project

The area of the SONY forest is over some 10,000 square meters surrounding of a new office building site of SONY, located in the redeveloped area near Osaki Station, Tokyo, Japan. The new office building is designed by Kazuhiko Yamanashi, who installed a façade system called ‘Bio Skin’ developed by Nikken Sekkei and TOTO. Bio Skin is made of ceramic with water pipes inside to reduce heat island effects by flowing water. The site for this project is a gently rolling hill with 10 meter difference in altitude. The goal of the project was to create a ‘natural’ forest around the SONY building. To this end, we developed the SS system. In this section, we present the components of the SS system together with the design process of the SONY forest project.

3.1. DESIGN ‘NATURAL’

After the discussion about what kind of forest we should design, we decided to create a ‘natural forest’ rather than creating an artificial landscape. To embody the ‘natural forest’, we intensively discussed the following questions: how to

design ‘natural’?; does designing ‘natural’ contradict natural?; how to define a ‘natural forest’?

Finally, we came to the conclusion that the natural forest is the forest where visitors can feel natural. The design methodology of the SS system is not to mimic the layout of trees in forests in the real world but to use a system that simulates the growth process of a natural forest controlled by urban environments, biological rules and designer’s sense. The system consists of the following three design processes.

- **Process 1:** Find rules of environmental conditions.
- **Process 2:** Find biological rules.
- **Process 3:** Run the SS system to grow a forest using environmental parameters, biological characteristics of the plants and algorithms of plant growth.

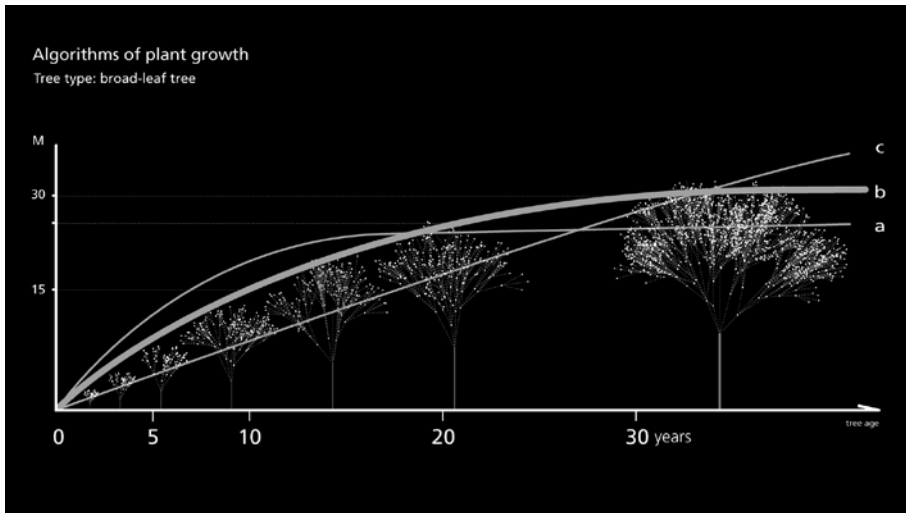
4. The seeds scattering system for the SONY forest project

4.1. FIND RULES OF ENVIRONMENTAL CONDITIONS

The first process is to survey the surrounding environmental conditions around the building project site, to construct their quantitative data and to convert them into an operational data set with a parameter set. In this project, we utilized the environmental assessments already carried out when the new office building was planned. Those assessments included natural environmental assessments, such as wind analysis, lighting analysis, soil conditions, and urban environmental assessments, such as pedestrian flows and traffic volumes.

4.2. FIND BIOLOGICAL RULES

The second process is to select plant species for the project site, to survey the biological characteristics of the selected plants, and to develop algorithms of plant-growth (Figure 1). The biological characteristics include suitable environments for every species of plants, and acceptable and critical values of environmental changes.

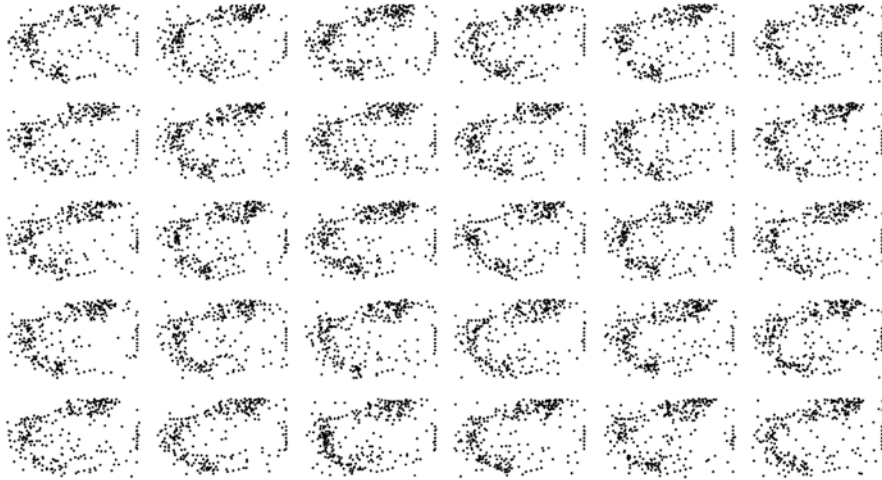


4.4. FIVE PROGRAMINGS TO GROW THE FOREST

The final process is to run the SS system incorporating the above-mentioned parameters, the data of biological characteristics of the plants and the plant-growth algorithms. In running the SS system, we grew the forest by controlling parameters and optimizing many environmental factors. It should be noted that this process is not the simulation of a forest growth process but rather a design process, because the parameter control and the optimization are based on biological rules as well as designer's rules. The advantages of the system are that designers can deeply understand about environmental conditions and biological rules, and that they can integrate design senses in the forest-growth process. The process consists of the following six steps.

4.4.1. Step one: Scattering seeds

Step 1 is to scatter seeds randomly according to a certain rule. Each seed contains the data of environmental conditions such as the amount of light, wind strength and so forth. By scattering seeds repeatedly, we can generate various layouts almost instantly (Figure 2). The possible variations are narrowed by the optimization processes in the following sections.



4.4.2. Analyze the distribution of seeds

Step 2 is to analyze the distribution of seeds with Delaunay triangulation, and to analyze neighbourhoods of the seeds determined by the Voronoi diagram generated by the seeds.

4.4.3. Natural selection program

Step 3 is to run the natural selection program that optimizes distances between seeds.

4.4.4. Generate plant communities and paths

Step 4 is to determine the distance between seeds to create clustered communities of plants. Foot-paths are generated in empty areas between the clustered communities. Because these paths are located farthest from the feet of trees, plant roots can be protected from human activities, and also the paths can be protected from being destroyed by the growth of roots.

4.4.5. Optimize the composition of plant species

Step 5 is to optimize the composition of plant species in response to the final layout of seeds (Figure 3).

4.4.6. Design in a four dimensional space

Step 6 is to grow the forest in response to the environmental conditions and plant-growth algorithms. The system can simulate and optimize future plant states at 10 years, 15 years, 30 years.... from now (Figure 4). We can design the landscape imagining the future forest appearance.

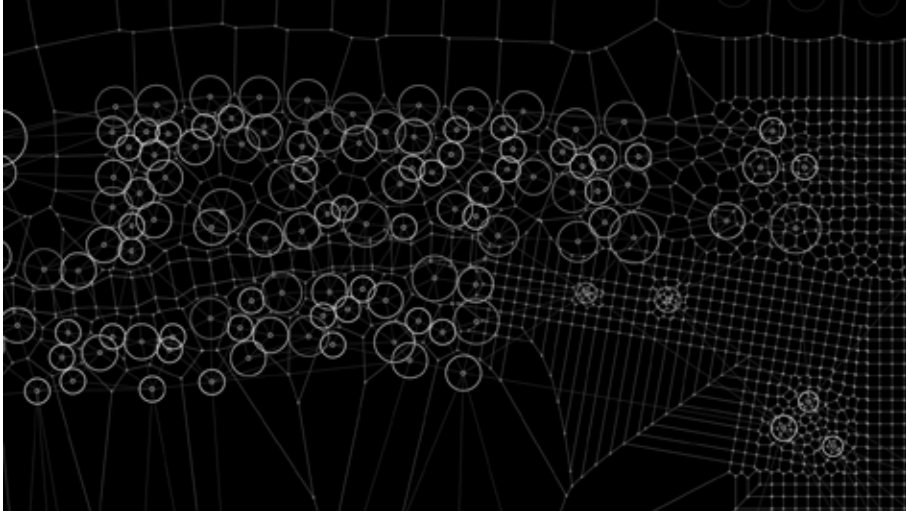


Figure 3. A part of the final plan for the SONY forest project.

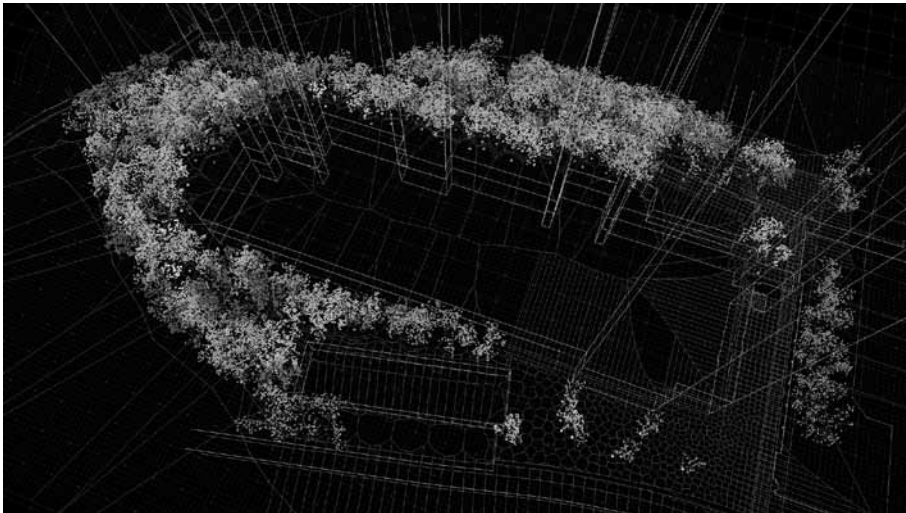


Figure 4. The forest appearance 15 years from now.

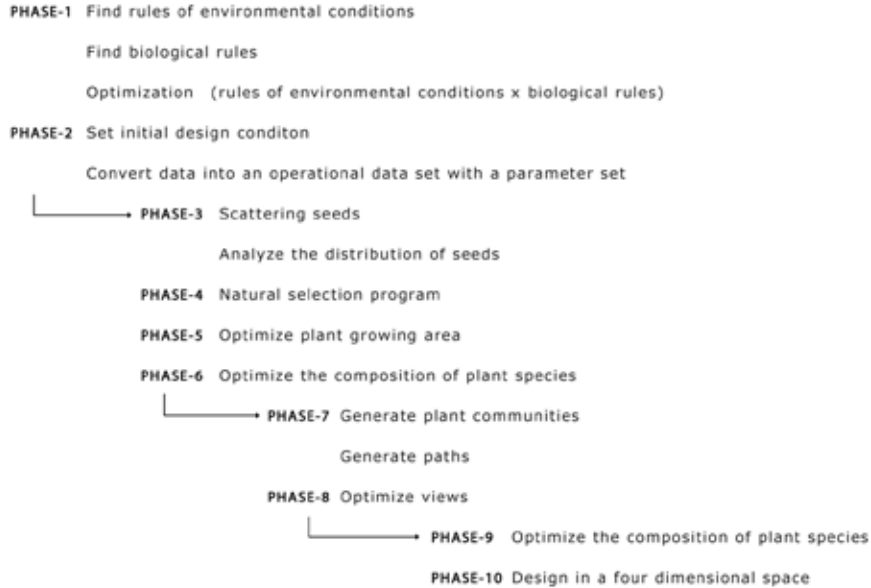


Figure 5. The whole design process in detail.

5. Conclusion

The construction of the physical plan in the landscape project started this September in 2010. At the end of November in 2010, there was an experimental occasion in which pedestrians could compare the layout of trees in our project site and that designed in a conventional way in the site adjacent to the project site. The difference was distinct. The pedestrians reported that in the newly designed site, they felt that the layout of trees was not merely random but meaningfully random reflecting the surrounding environments; this feeling was similar to the feeling experienced in the real natural forests.

In this paper, we proposed computational landscape design called the seeds scattering system. The SS system can manage environmental conditions, plant-growth and appearances of plants in an interactive manner in design processes. In addition, the system can manage a huge amount of data from environmental and biological researches. Designer's role in this system is not to manipulate geometries or compositions of trees but to design fundamental

rules behind them. As a result, designers can design landscape in an interactive manner, and produce the landscape inherent in its site.

A further direction of this project is to develop this system in such a way that it can manage real-time environmental data obtained from a real-time sensor network system.



Figure 6. The SONY forest in the urban context (The construction site on Nov.19th, 2010).

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GENERATIVE AND PARAMETRIC DESIGN II

06.	Digital catalogue: A computational implementation of Korean joinery system in the design of a transformable disaster shelter <i>Jason J. Kim and Hyoung-June Park</i>	61
07.	Digital tea house: Japanese tea ceremony as a pretext for exploring parametric design and digital fabrication in architectural education <i>Kaon Ko and Salvator-John Liotta</i>	71
08.	A new perspective to look at ice-ray grammar <i>Xiaofang Yuan, Jihyun Lee and Yu Wu</i>	81
09.	Form follows parameters: Parametric modeling for fabrication and manufacturing processes <i>Jonathon Anderson and Ming Tang</i>	91
10.	Supporting shape reinterpretation with eye tracking <i>Iestyn Jowers, Miquel Prats, Nieves Pedreira, Alison Mcay and Steve Garner</i>	101

DIGITAL CATALOGUE

A computational implementation of Korean joinery system in the design of a transformable disaster shelter

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Abstract. With the help of Building Information Modelling (BIM), the digital catalogue of all the 44 components of Korean joinery system is developed for the application of their tectonic principles in the design of a transformable disaster shelter. Based upon the components of three primary bracket styles (Jusim-Po, Ik-Gong, and Da-Po) of traditional Korean joinery system in the catalogue, the parametric modifications of the components and their rearrangements are performed for various iteration of the disaster shelter. The usage of Korean joinery system in assembling and disassembling the components enhances the transformability and the reusability of the shelter. This paper demonstrates the computational implementation of Korean joinery system and the design process of a transformable disaster shelter.

Keywords. Digital catalogue; BIM; Korean joinery system.

1. Introduction

With the increasing concern of natural disasters, continuous studies on emergency relief shelters have been actively promoted and provided the development of prefabrication method and assembly system of the shelter. However, one of the disadvantages of current disaster shelter designs lies in its after usage. Numbers of projects revealed the inconvenience of the structure after the usage such as required storage areas, auctioning of the product, recycling process and littering of the materials. The significance of this research is in maximizing the reusability of the building components through their parametric changes and rearrangements with applying traditional Korean joinery

system.

Traditional Korean architecture is referred to as “moving architecture” that allows the reuse of building components with its flexible joinery system in assembly and disassembly process and prefabrication method. All the 44 components of Korean joinery system become a series of modules in a digital catalogue. The components of the digital catalogue were built within Building Information Modelling (BIM) environment. The digital catalogue allows a user to explore various morphological transformations in building components and its design iteration through the parametric changes and rearrangements of joinery components saved in the catalogue. The parametric conditions in BIM allow flexible changes in form, dimension and assembly of the components. The unique setting of working with the components, BIM software allows its users to easily modify the general characteristics of components through their parametric changes (Lee, Sacks and Eastman, 2006). The aim of the study was focused on the possibilities of parametric design using BIM system for industrialization of modernized Korean traditional buildings (Kim et al, 2010). The studies of construction methodology of traditional Korean architecture from the bottom-up process using BIM software was achieved during the research.

In this paper, the implementation of the digital catalogue is introduced in the process of making various transformation outcomes of a prototype disaster shelter.

2. Disaster shelter

The typology of disaster shelters can be divided into general system and movable system (Moon and Lee, 2006). The general system is such as paper-tube structure and ferroconcrete structure for long term usage according to climate and nature feature. The movable system defined as the use of mobility and flexibility, light weight and economical efficiency. The only concern is the matter of supply and efficiency. Disaster shelters are no longer useful after the disaster end (Lee, Kim and Lee, 2004). In some cases, disaster shelters are being disposed and the disposed components become another hazardous atmosphere onto the site. FEMA disaster trailer was effectively distributed during hurricane Katrina. The immovability and prefabricated structure was able to mass-produced and delivered onto the site in a short period of time. However, its prefabricated materials caused health problem by polluting the interior air through the hazardous levels of formaldehyde used in its premade materials. Also mass production of the product flooded the market after its use, where trailer business dumped their products. The development of reusable components is very significant that such flexibility and mobility in the modification of the shelter can be achieved through components reassembly.

3. Traditional Korean Joinery System

The advanced tectonic principles of individual components embedded in traditional Korean joinery system effectively led to an easy assembly and disassembly, fast construction, easy relocation of a structure and the reuse of components (Chong, 1974). Traditional Korean architecture is not a one massive structure but multiples of individual components assembled together. The wide varieties of joineries effectively led to easy assembly of the components. The case of repairing works in traditional Korean architecture depicted its quality of reusability of the components and relocation of a building structure. Traditional Korean wooden structures used bracket system as a main structural element in a building. Bracket system where different members are assembled through various joineries needs not only its strength in each member but also strength in those of joining connections. (Kim, 1993). In this paper, categorization of joinery resulted in focusing on a specific unit in traditional Korean architecture-the bracket systems.

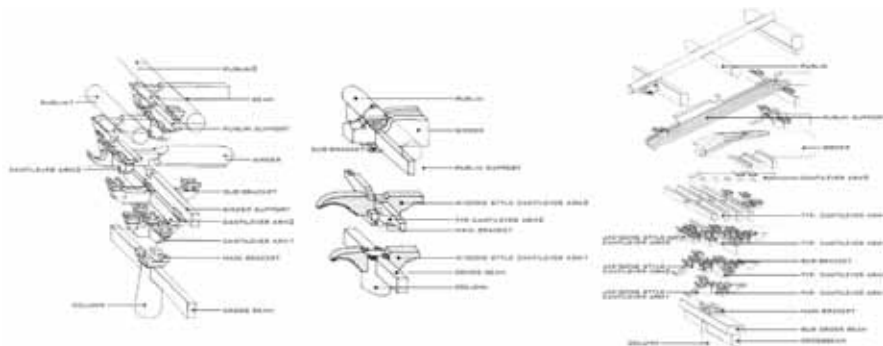


Figure 1. (a) Ju-Sim-Po, (b) Ik-Gong, (c) Da-Po

The three main types of bracket systems found in traditional Korean architecture are Ju-Sim-Po style, Ik-Gong style and Da-Po style of bracket system. Ju-Sim-Po style as the first bracket system introduced in Korea was favourable with its simple construction with relatively strong support. Ik-Gong style articulated the beauty of form through creating a simpler version of Ju-Sim-Po. Da-Po style was the most complex system with added number of components which enable to support heavier roof structure. Especially in the case of traditional wooden structures of Korean architecture, flexible joinery and connections in building components benefit effective relocation of its building to other site through dismantling the components.

4. Digital catalogue

Jean-Nicolas Louis Durand (1760-1834) investigated on the system of design using simple modular elements in the *Recueil et Parallèle des Édifices de Tout Genre*. Comparative taxonomy, a table of architectural species introduced in the *Recueil* created a basic foundation of the digital catalogue where the idiosyncratic objects emerged from manipulation of architectonic elements during the form-making process. The comparative taxonomy in architectonic elements through the parametric modifications on existing components can generate various iteration of form making process of the disaster shelter. The wide varieties of traditional Korean joineries were selected as the main component family to be modified.

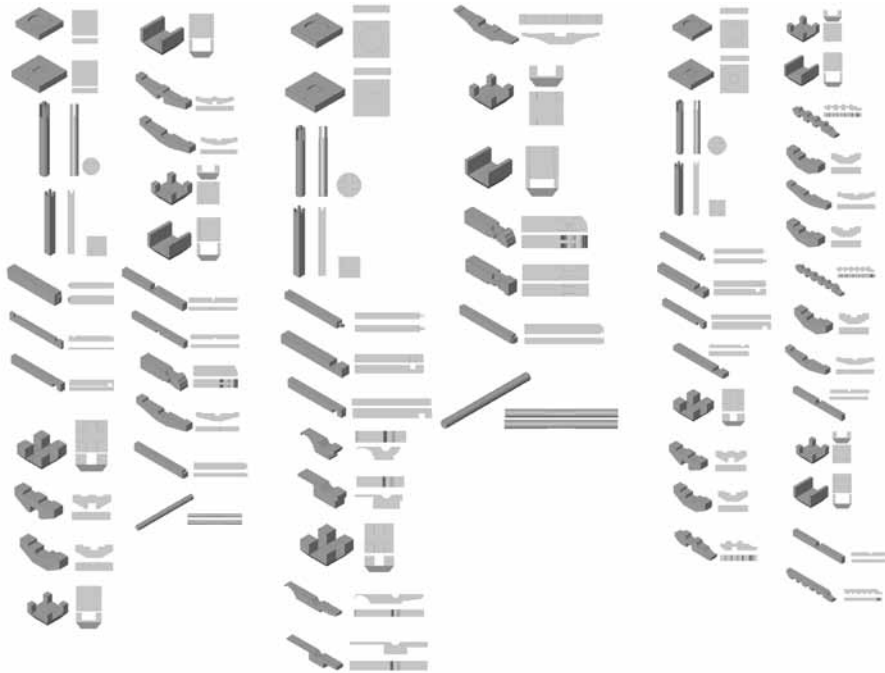


Figure 2. Existing component group J, I and D (constructed in Revit Architecture)

Total number of the 44 existing components was created from *Ju-Sim-Po*, *Ik-Gong* and *Da-Po*. All the components become a series of modules in the catalogue for their parametric changes and rearrangements within Autodesk Revit environment. Any single module or the combinations of the multiple modules from the catalogue can be employed for easy fabrication, removing, reattaching and acting as a reusable structural element.

4.1. METHOD OF CATEGORIZATION

Joineries were categorized under four groups based on the function and its use in existing traditional structure. The four groups are floor, column, brackets and roof. Categorization of components enhances the usability of the components in building construction. By categorizing each component to its function, a user can have clear understanding in selection of each component. The existing components will be divided into three main types of bracket systems: group J for *Ju-Sim-Po*, group I for *Ik-Gong* and group D for *Da-Po* styles.

Table 1. Labelling of existing component groups

Component group Ju-Sim-Po	Component group Ik-Gong	Component group Da-Po
J_01 ~ J_15	I_01 ~ I_11	D_01 ~ D_17

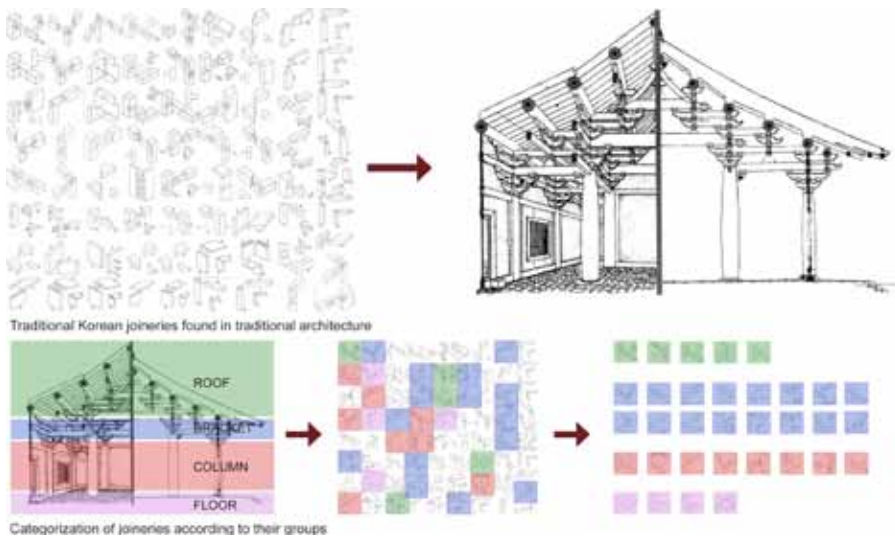


Figure 3. Categorization of joineries according to function in traditional architecture

4.2. DEVELOPMENT OF BASIC MODULES

The existing components shown in Figure 1 were created in Revit environment as 44 basic modules for the construction of a shelter under the parametric settings of constraints. Groupings of existing 44 components were based on their function in traditional Korean wooden structure: floor, column, bracket and roof.

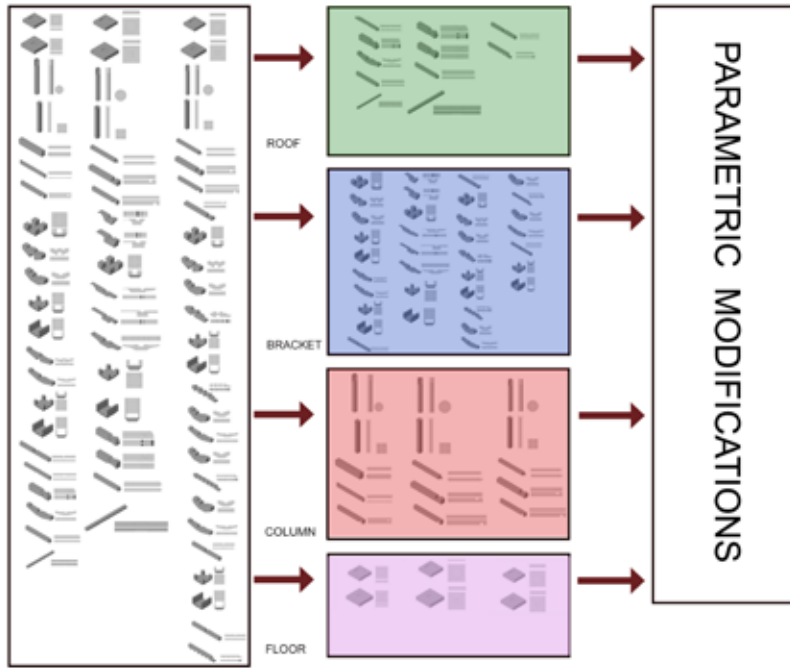


Figure 4. Categorization of existing components

4.3. COMPONENTS MODIFICATION

The idea of generating new components is to cross reference these restrictions in existing components. By adding the values of different joinery types between mortise-and-tenon joinery and simple lap-joinery, usages, locations of joinery and piercing of the component, existing components require its changes in form and dimension through parametric modifications (Namgoong et al, 2008). In the proposed catalogue, an individual component in the joinery system is defined with four design factors such as 1) joinery type, 2) use of joinery, 3) location of joinery, and 4) piercing of the member. With modifying the contents of each design factor, the user of the digital catalogue is able to generate a new component. According to user's preference, the component parameter can be substituted to change the form and its relationship to the assembly units. For example, when the changes of the design factors in the given component are made as in table 2, a new component is generated as shown in figure 5.

Table 2. Labelling of existing component groups

Type of joinery	simple scarf joint	mortise and tenon joint
Use of joinery	rectangular lumber + board	rectangular lumber + rectangular lumber
Location of joinery	end of lumber + end of lumber	inside of lumber + inside of lumber
Pierce	none	present



Figure 5. Demonstration in change of joinery type, use, location and pierce

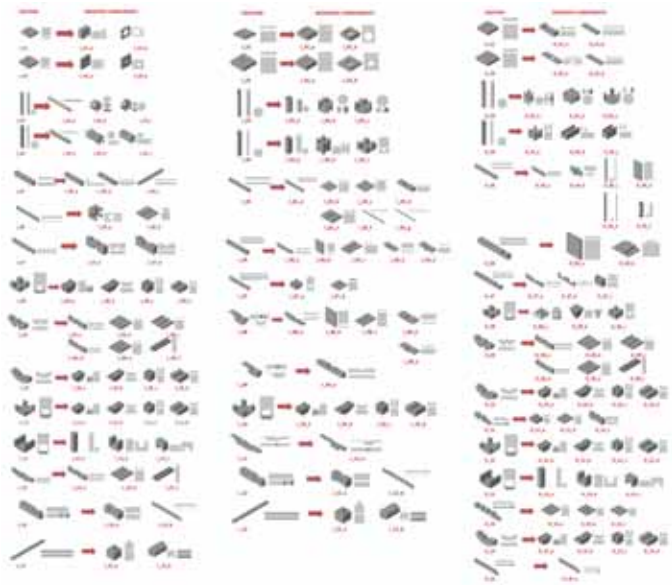


Figure 6. Total number of components in digital catalogue

Each of total 44 components in group J (*Ju-Sim-Po*), I (*Ik-Gong*) and D (*Da-Po*) were modified accordance with the changes in four design factors of each component. From original 44 components, total numbers of 180 components were generated in digital catalog as shown in figure 6. Modified components will be grouped correspond to their mother component. For example, modified components generated from the existing component in floor group

will remain in same group category. Each existing components with its modified components will be grouped under four main categories: floor, column, bracket and roof. However, the modified components changed its function and dimension through the parametric modifications of the four categories. Therefore the components need to be regrouped according to their new function and performance. Figure 7 indicates the reshuffling of the components that have distinct forms and dimensions unlike the rest of the components under the same grouping. The evolving of the component and its new generative constructions now cross reference the components function and its dimension.

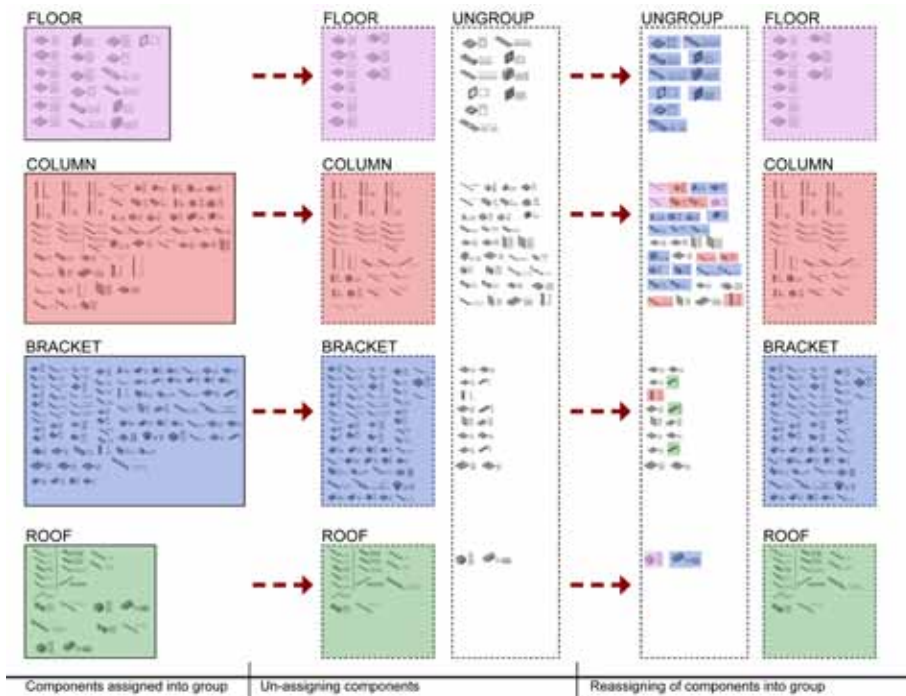


Figure 7. Reshuffling of components according to the function and dimension

Grouping of the components accordance to the function can guide the users to easily pick and choose the component to be applied during the design process. Wall/floor panels group was added to the original four groups such as floor, column, bracket, and roof, in the process of generating total 180 components with changing the design factors of the original 44 components.

5. Transformations

Design of prototype shelter was made through assembly of components in five groups (floor, column, bracket, roof, and wall/floor panels) under the digital catalogue. By analyzing individual components with its connection and method of construction, specific types of components were chosen for experimentation. A prototype of disaster shelter is designed with 17 component types and 80 individual components as shown in figure 8.

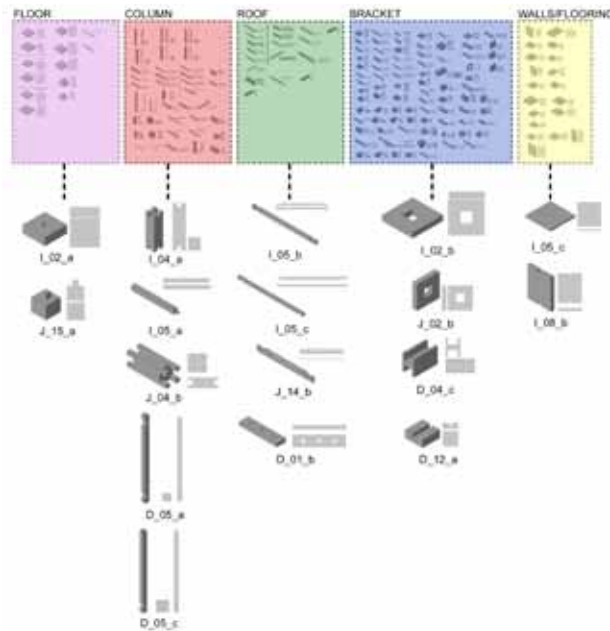


Figure 8. Components used in the design of a prototype disaster shelter A

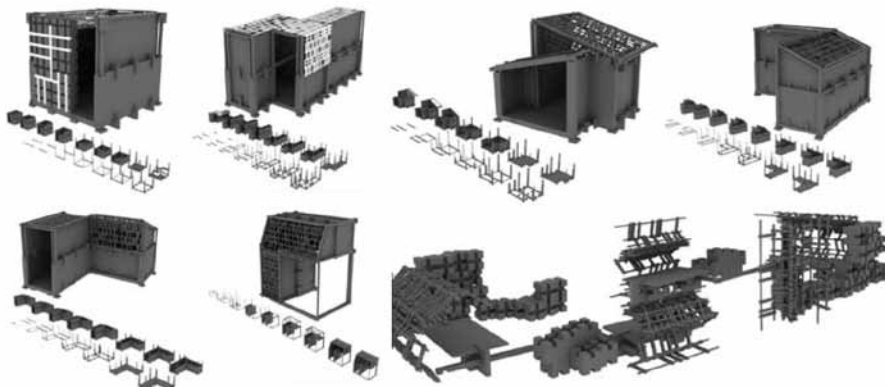


Figure 9. Morphological transformation of a prototype A (top-left) into others

The assembled prototype A can be dismantled and recreate as a sub-units or furniture layouts. It transforms into a different prototype as shown in figure 9. Not only the shelter design changes its form into sub-structures but also it can change its form as a shelter design such as through adding and subtracting extra components.

6. Discussion

In this paper, digital catalogue was utilized in the design process of a prototype disaster shelter. With the use of 17 components from 5 categorized groups, prototype design can be transform through the reconfiguration of the components. In fig. 9, structure not only transforms into another form of structure but also various furniture layouts can be produced. Design of furniture or individual resting units can be effectively used for the public after use of the shelter. Morphological transformation of a disaster shelter through the application of traditional Korean joinery system was performed to suggest a flexibility and mobility in a prototype disaster shelter design. It shows the possible application of BIM parametric environment in prefabrication and individual component generation. The significance of digital catalogue is in that each component can be user dependant. The catalogue allows a user to assign various parameters to the variables of each component according to its usage. By assigning different parameter, the component has flexibility for generating various joint connections enhancing the morphological transformation of a prototype shelter design.

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DIGITAL TEA HOUSE

Japanese tea ceremony as a pretext for exploring parametric design and digital fabrication in architectural education

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Abstract. This paper reviews the Digital Tea House, a joint workshop in August of 2010 held at the University of Tokyo, Department of Architecture, together with Columbia University GSAPP. Three pavilions for hosting ceremony were designed and built in less than one month, in an attempt to bridge technology and culture not only through design but also fabrication. Issues addressed in the process included applications of computational design, interpretations of tradition and culture in spatial or activity oriented expressions, structural stability, to practical solutions for quick physical materialization. Three teams comprised of 6 to 8 students, each a blend of different nationalities, ultimately produced 3 full-scale tea houses with the same software, primary material, budget, and principal fabrication method.

Keywords. Digital fabrication; academic workshop; computational design; design-build; tea house.

1. Introduction

Digital Tea House is a joint workshop held at the University of Tokyo, Department of Architecture, together with Columbia University GSAPP, with the aim to design and build three pavilions for hosting tea ceremony. The three-week workshop is an attempt to bridge technology and culture not only through design but also fabrication. A wide range of issues was addressed in the process from applications of computational design, interpretations of tradition and culture, structural stability, to practical solutions for quick physical

materialization within limited time and budget.

The workshop was divided into two parts: First part introduced computational logic and concepts, which led to the second part where explorations related to Japanese tea ceremony culture served as a pretext for further exploring digital design and fabrication. Three teams, each comprised of 6 to 8 students, ultimately produced three full-scale tea houses to test out their concepts, methodologies and materials. Baseline for common software (Rhinoceros and Grasshopper), principal material (50 sheets of 9mm and/or 12mm thick 3x6 plywood), fabrication method (CNC routing), and budget (up to 150,000 JPY, approximately 1,500 USD, per team, excluding plywood and CNC fabrication costs) served to make comparisons and analysis during the process and later in three distinct outcomes.

1.2. TEA HOUSE AS CULTURAL BACKDROP

“The Japanese people in the 16th century created new culture which consisted of such elements as the ‘Tea House,’ ‘Sukiya Style Architecture’ and the ‘Wabi-Sabi’ aesthetic of transience. What these people did can be considered a reorganization of all products where the body is used as the reference. [...] They thought that relying on anything else as the reference would only add to the confusion. Therefore, they mercilessly discarded the traditional standards and cultural hierarchy that was used in Japan to that point. The ‘Tea House’ represented an exceedingly avant-garde type of architecture at the time”¹.

From the reference to the body, the tea house evolved into a microcosmic situation where host and guest(s) meet and at the same time an intellectual device through which one is made aware of the natural phenomena occurring outside. The traditional tea house is composed of a variety of elements, including *shoji*² screens or bamboo slats that serve as light filter that underscore gradations of light. In addition, a small wooden sliding door at *nijiriguchi*³ entryway, *tatami* mats that signify where one may sit, and a recessed alcove *tokonoma*⁴ for hanging scroll and flowers are typically incorporated.

2. Pedagogic approach and significance

The workshop provides a point of reflection within the academic setting to consider consequences of computational design when applied to physical reality of making, rather than stressing on the form-finding aspects of computational design. The pedagogic significance lies in the engagement of a continuous process, with a constant feedback loop between the software and material characteristics as a process of operation. As a result, each of the pavilion’s physical presence and their feasibility on multiple levels could be evaluated

and reconsidered throughout. Such process is subject to simultaneous assessment of technology and working with the highly sophisticated parts it can produce.

Yet for most students, inexperienced in construction, the temporariness of pavilions relieved them of some issues, including protection from weather, foundations, and structural stability over an extended period of time. It also encouraged material experimentation, intuitive predictions for structural elements, and trial and error approach in detailing and assembly.

2.1. PRACTICABILITY OF PARAMETRIC DESIGN

Among architectural design students at the university, the emphasis is placed too often on the strength of concept with little regard to how the project may develop into actual construction or relate to its immediate context. The result can be an outlet where anything goes, whether unrealistic or unrelated to issues of economy, society, or culture. The use of parametric design can possibly promote this tendency, where students can easily produce forms too complex to control.

Constraints including structure, material, budget, time, assembly, site, and function help avoid the risk of designs that are impossible to be realized. For instance, students coped with possible spans of given plywood structure while considering how long they would have to be temporarily supported during assembly. As a combination of creativity and technical means, architectural design is incoherent without one or the other. When parametric design is integrated into a process with framework of real-life constraints, its advantages are beyond mere stylistic choices or visual effects.

For the duration of the entire process — from design, manipulations, detailing, to fabrication — it became apparent that the use of graphical algorithm editor tool allows for instantaneous modifications and influences on architectural conditions and context. At the same time, there is a tendency for oversimplification in such model: When a single line, for example, is further manipulated into endless variety of forms and surfaces, it alone can seem to substitute complex architectural elements. How would these simple manipulations translate to construction? What would this diagrammatic and methodical approach produce when combined with a culturally meaningful function as a tea house?

2.2. FROM CONTEXT-NEUTRAL TO CONTEXT-AWARE DESIGN

How can we bridge the digital environment to the physical environment in which we live? First, the consequences of the designs need to be addressed,

in how every part should to be considered for strength, weight, its assembly sequence, and surface treatment. There are also questions regarding appropriateness and scale of design, which often cannot be resolved in the isolated modelling phase. How to reconcile the disparities is one of the biggest challenges in the learning process; this workshop uses a cultural function of the Japanese tea house as a starting point to address the gap. The often scale-less nature of design through scripting is applied via traditional set of rules to be physically implemented. The development process from context-neutral idea to context-aware architecture calls for multidimensional views.

3. Digital tea house case studies

Three case studies are described in the following sections. Pavilion ‘Nami-no-ma’ translated the textures and shape of a tea bowl to linear layering of the plywood, while pavilion ‘130008252010’ focused on light patterns and transparency. In pavilion ‘Poetry and Parametrics’ reinterpretations of traditional rules were applied more literally.

3.1. PAVILION “NAMI-NO-MA (SPACE OF WAVES)”

Guided by strong aesthetic characteristics from the tea ceremony, the expression of the beauty and imperfection of nature is translated to plywood, which surrounds the basic 2-tatami traditional layout of the interior space. Tea house typically offers limited level of openness to the outside; in this interpretation, the varying thickness of the wall becomes the boundary between the tea ceremony taking place inside and the surrounding nature, while the views are controlled by the density and bending angle of each layer. The undulating waves also facilitate functions of *tokonoma* and *nijiri-guchi*, where the largest opening in the pavilion is structurally reinforced beneath the lower curvature to support body weight.



Figure 1 (left). Pavilion “Nami-no-Ma.” Figure 2 (right). Interior view.

Efforts to create a more natural and flowing form from the 3-axis CNC routing, which is a flat surface manufacturing, pushed for experimentations with half-depth grooves in specifically calculated patterns on the 9mm plywood. The key challenge was in achieving the desired bend in a continuous curve following a circular geometry of the plan. Enabled by close communications with CNC router operators, tests initially began with grooves of different depths and stitch patterns of varying lengths. The triangulated grooves eventually proved to be the ideal solution for 3-directional curves to be fixated on site, whereas perpendicular grooves only enabled 2-directional bending per panel. The resulting pavilion is a soft envelop for the interior activity, accentuated by modest connections to the surrounding environment.

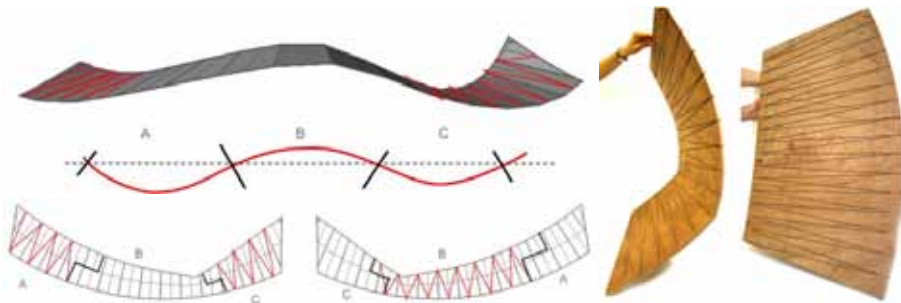


Figure 3 (left). Groove patterns and densities were determined according to the desired bending, while joints were placed strategically to create a continuous curvature. Figure 4 (right). Tests of the groove patterns and bending characteristics with plywood were conducted.

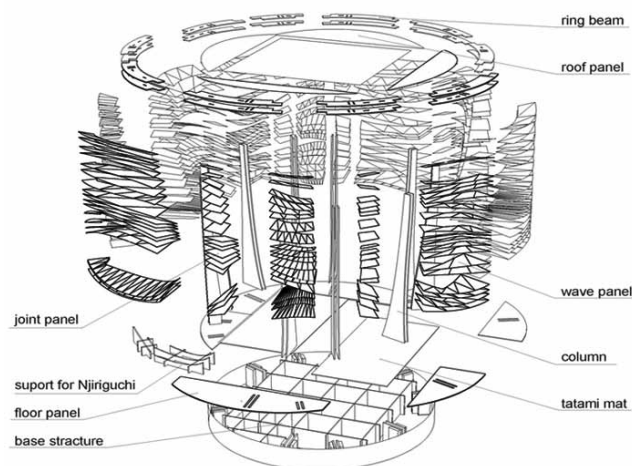


Figure 5. Axonometric drawing shows composition of parts.

3.2. PAVILION “130008252010”

Designed for the precise moment of 13:00 on Aug. 25, 2010, when the tea ceremony took place, the interior space is planned for specific lighting condition where fragmented shadows align with the cut-out straw mat floor pattern, serving as ever-changing ornament but also indicating where host and guests may sit at the aforementioned moment. Angles and depths of 192 triangular patterned sun-shading units over a semi-conical arch structure, leaning forward at 35.5 degrees that is the latitude of Tokyo, have been designed with considerations for the passage of time and changes in sunlight.



Figure 6 (left). Pavilion 130008252010. Figure 7 (right). Interior view.

The external surface of the pavilion is a smooth continuous curvature while the internal surface is irregular, with varying depths of the triangular units. These units posed a challenge in terms of connections due to their wide range of angles; finger joints resolved the issue by increasing the contact surface area, but these joints would have been considered differently with a 5-axis router or a different tool to enable smoother edge conditions where as many as seven angles congregate. Corresponding angled fins made of laser-cut white translucent paper-plastic laminate inserted into each unit further regulated desired lighting conditions. However half of the fins were lacking in the end because of miscalculation of time; while parametric manipulations are almost instantaneous, physical realisation through labour takes much longer.

Pavilion ‘130008252010’ is essentially a shading device, materialising the natural phenomenon of daylight through their tea house. It is a way of visualising something as ephemeral as light via incorporation of the 4th dimension, time, by utilizing parametric software. Although traditional sequential and spatial considerations were somewhat sacrificed by its singular focus, it was also very poignant within the ever-changing interior conditions.



Figure 8 (left). Plywood panels ready for assembly. Figure 9 (right). Assembly process.

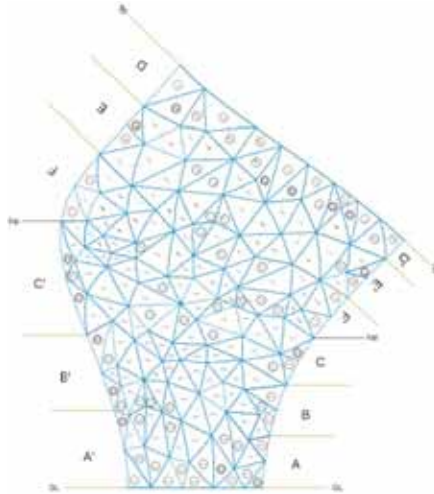


Figure 10 (left). Surface map showing all triangular units, which were divided into alphabetical zones for organization. Figure 11 (right). Exploded isometric.

3.3. PAVILION “POETRY AND PARAMETRICS”

Students from GSAPP focused on the choreography of the tea ceremony sequence by pushing the aspect of parametric design to translate the traditional tea ceremony sequence of separate host and guest entries. Attractor points organized the interior space, each designating a field of influence: Positions of host, two guests, and the *tokonoma*. The spiralling boundary contains the activity within the two *tatami*-mat space. The idea for the design began with one simple module, which can be used to create the entire structural system and facade for the tea house.

Disjunction between limited amount of materials and the preferred geometry were reconciled in the use of parametric adjustments in the Grasshopper script. The method left room for play, which appears in a suspended radial roof enclosure inspired by origami folding and floor patterns created by grooves in the plywood resembling the stepping-stones surrounded by ripples. The wall panels also add to the diversity of surface treatments; the density of groove lines scored on the surface of the panels, either facing outside or inside dependent on the angle, visually indicates the positional deviations. The investigations relating to how the geometry and proportions are brought together in the assembly system.

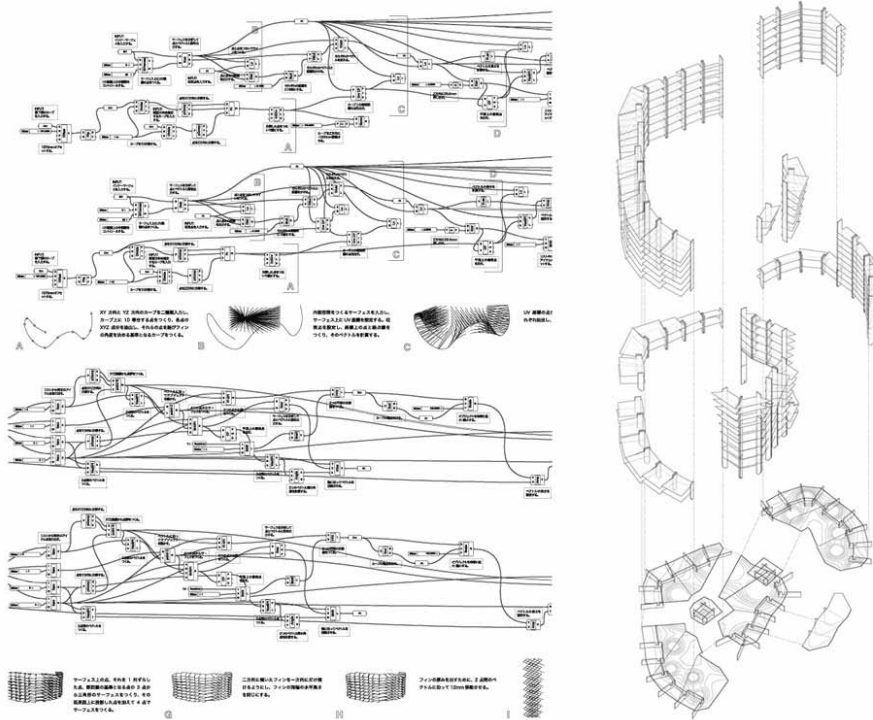


Figure 12 (left). Parts of pavilion “Poetry and Parametrics” Grasshopper file shows the evolution of parametric design. Figure 13 (right). Exploded isometric.



Figure 14 (left). Pavilion “Poetry and Parametrics.” Figure 15 (centre) View from above showing origami roof. Figure 16 (right). Interior view during tea ceremony preparation.

4. Conclusion

Conceived and finished in a very condensed period of less than one month, both computational design and digital fabrication enabled the speed and the challenges undertaken in each design. Every decision inevitably affected other aspects of the design and making at once, especially since each pavilion was designed to be movable and reassemble-able several times in other locations. Factors such as joints, or size and weight of preassembled parts, were considered throughout in this engaging process. Eventually students realized the importance of applying materials suitable for both design and fabrication process. Each factor proved to be a constraint that pushed students to look for creative and feasible solutions.

From a cultural point of view, the students brought back the spirit of tea house in a contemporary digital manner reviving the tradition of avant-garde. It points to the importance of implementing pedagogy with not only present technologies such as parametric design and digital fabrication, but also with culture. Through the workshop it was made clear that such traditional values combined with new digital technologies is not contradictory, as exemplified in the tea houses and enforced by the final tea ceremony held inside in the forecourt at the University of Tokyo. On the contrary, the projects of *Digital Tea House* proved to be successful in the interpretation of the long established tradition and aesthetic. Japanese sensibility retains its unmistakably unique character even when it is filtered through the use of these new tools.

Design has evolved alongside technology, with mutually beneficial relationship. The workshop has been a framework for assessment of design and available technology, both of which were then experienced and evaluated by

the students as well as the tea masters and guests. As a result of one of the most significant innovations initiated by parametric modelling software, students were ultimately able to extract, edit, and abstract the traditional aspects pertinent to their works and transform into their contemporary possibilities of what a tea house might be.

Endnotes

1. Fischer, V., Schneider, U.: 2008, *Kengo Kuma: Breathing Architecture*, Birkhauser, Boston, 10.
2. *Shoji* is a vertical screen, typically composed of Japanese *washi* paper stretched over delicate wooden frame.
3. *Nijiri-guchi* refers to a small entryway specific to the tea house, approximately 60cm in both height and width. The tightness of the opening makes the guest crawl through with his or her head down.
4. *Tokonoma*, a small recessed alcove within a room where guests are received, is where flower arrangement and hanging scroll are commonly displayed.

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Students

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Team “Poetry and Parametrics”: Momo Araki, Yuval Borochoy, Jordan Carver, Rachel Hillery, Teel Lassiter, Lindsay McClelland, Kristen Munro, Michael Walch

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A NEW PERSPECTIVE TO LOOK AT ICE-RAY GRAMMAR

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Abstract. Chinese lattice designs are a rich source of interesting geometric forms and shape grammar has been used to analyze and generate Chinese lattice designs. Following the origin design intention, researchers have already defined simple and intuitively compelling shape grammar rules to generate them. However, for some self-similar ice-rays, it is difficult to clarify the design intention of them, which is why researchers still cannot define shape grammar rules for them. In this paper, we utilize the culture hints to select the lowest-level constituent for shape calculation and clarify the design intention embedded in the ice-rays. We develop our new shape grammar rules based on the design intention and validate the rules by generating an existing ice-ray window.

Keywords. Ice-ray; shape grammar; cultural hint; design intention; lowest-level constituent.

1. Introduction

Chinese lattice designs are a rich source of interesting geometric forms and shape grammars have been used as a means to describe the designs of the Chinese lattice. Daniel Sheets Dye catalogued various Chinese lattice designs constructed between 1000 BC and 1900 AD into 26 general types in his classic work *A grammar of Chinese lattice*. Some Chinese lattice designs in Dye's Grammar are regular patterns and some are irregular designs, like "ice-rays". Stiny (Stiny 1977) demonstrated that shape grammar can generate both types of the Chinese lattice designs in Figure 1: a periodic tiling and a self-similar ice-ray. However, for the self-similar ice-ray, stiny's grammar cannot generate all of them. There are still some ice-rays cannot be generate by shape grammar

and the ice-ray in Figure c is the one.

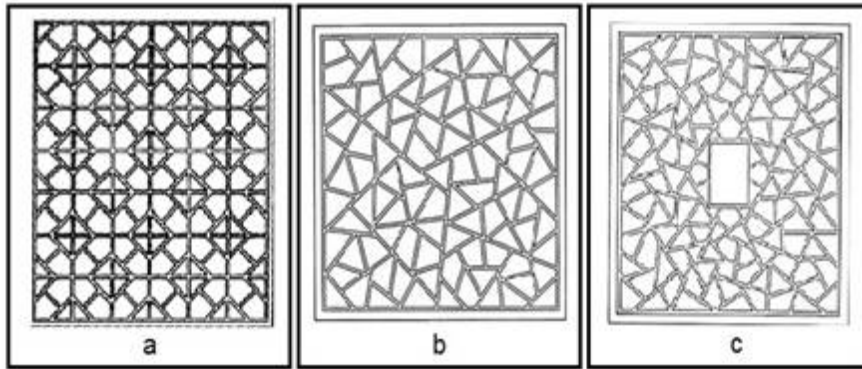


Figure 1. Three typical Chinese lattice designs a) a regular tiling; b) an irregular ice-ray, Chengtu, Szchwan, 1880; c) an irregular self-similar ice-ray

2. Background

Shape grammar has been used to define the language of designs such as ornamental art (Knight 1980; Knight 1981; Stiny 1977), architecture (Downing and Fleming 1981; Koning and Eizenberg 1981; Stiny and Mitchell 1978) and landscape design (Knight 1989; Knight 1990; Stiny and Mitchell 1980), transforming the verbal conventions of the composition into explicit visual shape rules. When the researcher defines the language of a design, he tries to find out the design intention and describe it by shape grammar rules. Koning and Eizenberg (1981) developed parametric shape grammar rules that can generate the composition and specify the function zones of Frank Lloyd Wright's prairie-style houses. In their word, the grammar they developed can be viewed as a formalization and elaboration of Wright's compositional principles for prairie-style houses in many ways. Moreover, they declared that the development of the grammar clarifies their understanding of the composition of Frank Lloyd Wright's prairie-style houses. Stiny's grammar can generate ice-ray designs in a very simple and intuitively compelling way (Figure 2). When Stiny described the ice-ray designs, he also tries to investigate the conventions used to construct Chinese ice-ray designs and develop the parametric shape grammars that can describe the making process.

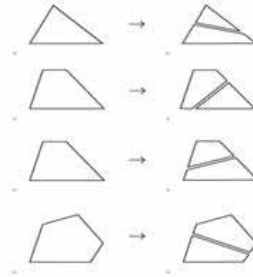


Figure 2. Stiny's shape grammar rules for ice-ray

Later, for the ease of computer implementation, Tapia (Tapia, 1992) generated new shape rules for the ice-ray designs (Figure 3). He followed the design intention Stiny used to describe ice-ray designs and he considered the way to implement the shape rules in computers. Liew put his focus on the dependency between shape grammars and computer implementation and categorized shape grammar rules for the Chinese ice-ray designs into 4 sub-categories: 1) simple parametric grid shape grammar rules; 2) parametric shape grammar rules; 3) constrained parametric shape grammar rules; and 4) unknown shape grammar rules. The ice-ray design c in Figure 1 belongs to the fourth which cannot generate by existing shape grammar rules.

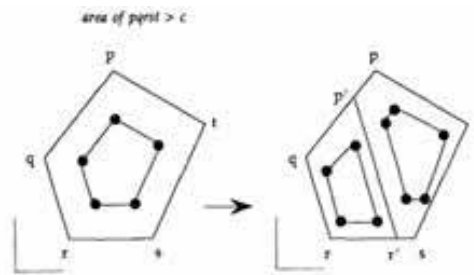


Figure 3. Tapia's shape grammar rule for ice-ray

The mentioned researches about Chinese lattice designs all follow the design intention described in Dye's book and their shape grammar rules cannot cover all the ice-ray designs. In this paper, we argue that Dye's understanding on Chinese ice-ray design is not completely correct. We try to find out the design intention embedded in the Chinese lattice design by utilizing cultural hints and define new shape rules that can generate the ice-ray designs.

The rest of the paper is organized as follows. In Section 3 we try to decompose the lattice pattern with different lowest-level constituents and argue the connection between the constituent and cultural hints and hypothesize the

design intention of Chinese lattice. In Section 4 we define and validate shape rules based on design intention. Finally, we conclude with discussions and future research direction.

3. Design intention embedded in Chinese lattice design

We choose the Chinese lattice window in Figure 4 as an example to find out how to decompose it into the lowest-level constituent and the design intention embedded in it. At first, we define the shape rules and the corresponding lowest-level constituent that can generate the lattice pattern. Then, the meaning of lowest-level constituent will be examined to trace the design intention embedded in the lattice window.

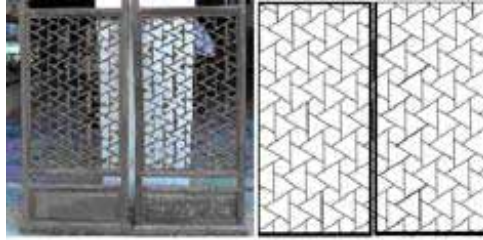


Figure 4. A Chinese lattice window

3.1. THE LOWEST-LEVEL CONSTITUENT FOR CALCULATION

The chosen window can be categorised into checkerboard design. Stiny used two schemas for the checkerboard designs. The first one is $x \rightarrow x + t(x)$ to produce the checkerboard pattern and the second is $x \div t(x)$ to inscribe the given motif and divide squares (Stiny, 2006, p331). The chosen window can be generated by using stiny's schemas if we choose one of the motifs as shown in Figure 5.

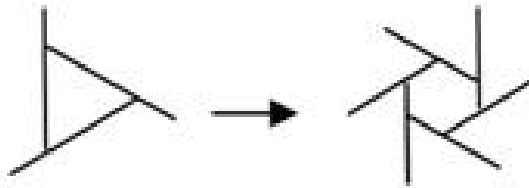


Figure 5. Two motifs for generating lattice window

It is very interesting to find that the chosen window can be generated by two different motifs. But this raises the problem. Which one can represent the

design intention embedded in the lattice window?

This problem rises every time when you calculate with shape. When we divide the shape into the lowest-level constituents, we can segment shape into lowest-level constituents in many different ways. This causes the questions like which way of segmenting shapes into constituents make the most sense in terms of what we want to calculate? Which analysis works best? Stiny suggested that we can dynamically change the constituent while we make the rules until we find the suitable one that can help calculate the shape. In the book “Shape: Talking about Seeing and Doing”, Stiny illustrated the problem about decision making when he faced several choices to segment the shape. He thought it is critical to choose the suitable way to divide shape into the lowest-level constituents, especially when someone is dealing with the design problem (Stiny, 2006). He pointed out that the way to choose the constituents to segment the shape depends on the rules he used and gave an example to show his idea (Figure 6).

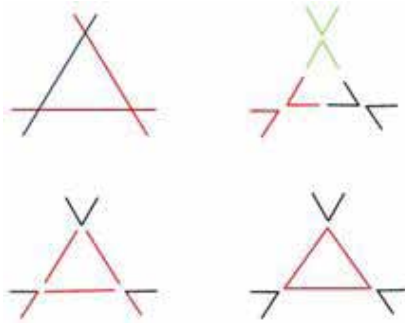


Figure.6. Four different ways to segment the triangle

3.2. THE CULTURAL INFORMATION IN THE PATTERN

When we treat the window as a checkerboard design, the motif becomes the lowest-level constituent to calculate. We do not use rules to describe the motif and we may miss the information in it because it is merely considered as a shape. Design is an intention activity and design intention will be influence by cultural context inevitably. While many cultures create designs with geometric patterns, each has distinct motifs and symmetries. The pattern of Chinese lattice window may contain some cultural information which influenced the design intention. As Dye (1947) described ice-ray in his book *A Grammar of Chinese Lattice*.

I have described it [ice-ray] as the result of a molecular strain in shrinking or breaking, but more recent observations and photographs seem to prove

that it is a conventionalization of ice-formation which has become traditional. (Dye, 1949, page 298)

Ice-ray lattice is not merely the imitation of natural phenomenon and it has become the pattern which contains some cultural information and design intention. In this paper, we propose a new way to select the lowest-level constituent for calculation. We utilize the cultural hints that are related to Chinese lattice window to determine the lowest-level constituent. In doing so, we may find out the embedded design intention and describe it by shape grammar rules.

In Chinese traditional building of Huizhou region, we can find the special ice-ray pattern which consists of a hexagon in the centre named “XuanJi” in Chinese ornamental pattern and the “Human shape” composed by every two bars around the hexagon. The pattern is to show the emphasis of human and the harmony of human and nature.

Based on the understanding of the cultural information of the ice-ray pattern, we propose a new perspective to look at the design intention of it. The lowest-level constituent of the window should be the “Human shape” and when the Chinese artisan makes the windows, the design intention is to embed the “Human shape” in it.

It is not hard for us to find the “Human shape” in the previous motifs (Figure 7). To define the new shape rules for the lattice design, we should consider the “Human shape” as the lowest-level constituent and add one more rule to describe the process form “Human shape” to the previous “lowest-level constituent”.



Figure 7. The “Human shape” in the motifs

4. New grammar for ice-ray

In this section, we will define the new shape grammar rules for the ice-ray design and use them to describe the making process of a Chinese lattice design that cannot generated by existing shape grammar rules.

4.1. THE NEW ICE-RAY GRAMMAR

Our grammar contains two shape rules:

- **Rule1.** Put a hexagon in the centre.
- **Rule2.** Create “Human shape” by adding a bar on existing one.

For the rule1, the hexagon can be replaced by a triangle....The aim of this rule is to create “XuanJi” in the window pattern.

For the rule2, the length and angle of the adding bar vary in different situations.

The difference between our rules and Stiny’s is on the understanding of the design intention embedded in the ice-ray. When Stiny examined the ice-ray designs, he followed Dye’s understanding of the lattice design.

“In the case of the ice-ray pattern, [the artisan] divides the whole area into large and equal light spots, and then subdivides until he reaches the size desired; he seldom uses dividers in his work.”(Dye, 1949, page 17)

Stiny (1977) illustrated the design intention behind the ice-ray design as the following: “One can image a Chinese artisan, summoned to a building site; bring with him tools and implements and a collection of finely finished sticks. Shown a rectangular window frame, he is asked to create an ice-ray lattice. He begins his design by selecting a stick of the appropriate length and carefully attaching it between two edges of the existing rectangular frame...”

What Dye and Stiny described is the making process of the ice-ray lattice. The design intention embedded in it might vary. From the cultural hints we mentioned before, we can get a different understanding from the same making process. We can image the artisan’s intention is not to divide the areas but to add a bar to create the “Human shape” and for balance and aesthetics, he tries to keep the appropriate size.

4.2. VALADIATION OF NEW GRAMMAR

To validate our shape grammar rules, we will use them to generate the lattice window in the Figure 8. (The “bars” in the ice-ray designs are represented as single straight lines)



Figure.8. A Chinese lattice window from existing building

In the first step, the pentagonal shape is added in the centre of the window. Then, the “Human shape” is generated in the first layer. The whole process is

shown in Figure 9.

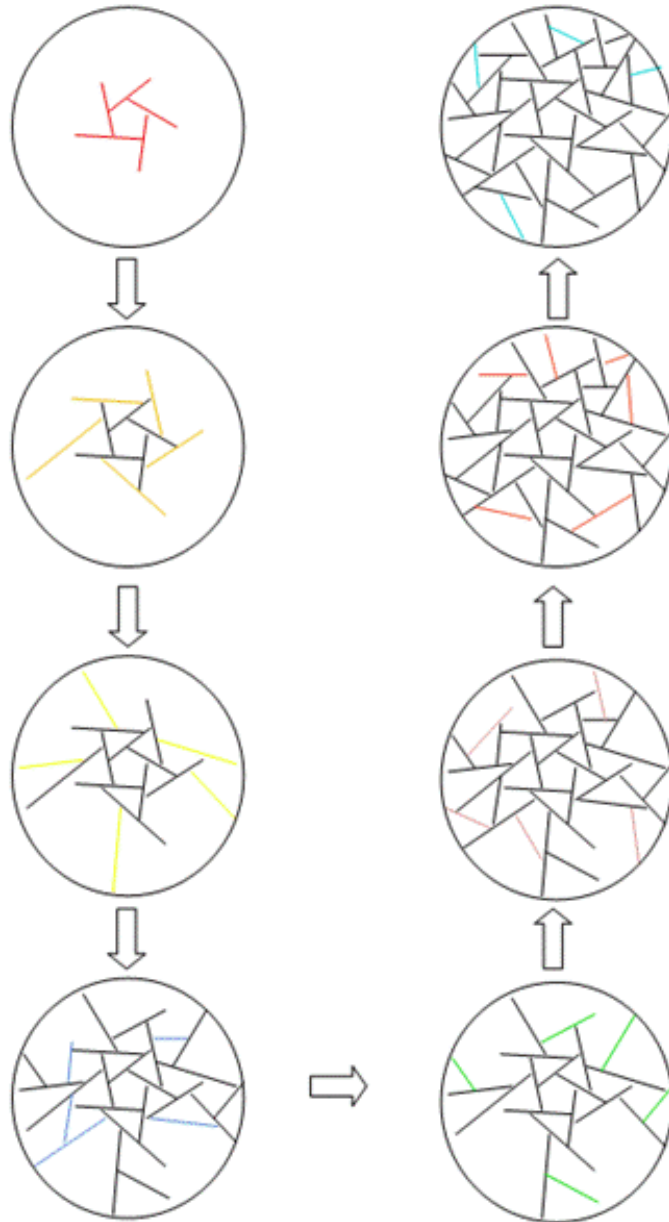


Figure.9. The generating process of by using new ice-ray rules

5. Discussion

In this paper, we try to describe the ice-ray designs by new shape grammar rules. We argue the inaccuracy of Dye's understanding on Chinese ice-ray design and propose new perspective to appreciate it by utilizing the related cultural information. Based on our understanding of the ice-ray design, we clarify the design intention embedded in it and develop our shape grammar rules follow the design intention. We validate our shape grammar rules by utilizing them to generate the ice-ray design.

Design intention plays a very vital role when we define the shape grammar rules. But sometimes it is difficult to clarify the ambiguous design intention of some artefacts because of the lack of literature. The cultural context can be utilized as hints to discover the design intention embedded. The concept of human and nature is very important in Chinese traditional culture and it can be found everywhere in the ancient Chinese artefacts. So we argue that the design intention of ice-ray is to build "Human shape" by two bars inside the window.

We demonstrate the process of generating the window by new shape rules. In the future, we will focus on the computer implementation of our shape grammar rules.

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FORM FOLLOWS PARAMETERS

Parametric modelling for fabrication and manufacturing processes

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Abstract. As the architectural field continues to explore the possibilities of parametric design it is important to understand that architectural computation has evolved from representations to simulation and evaluation. This paper explores the digital processes of parametric scripting as a way to generate architectural artefacts that can be realized in the physical landscape through various digital fabrication and industrial manufacturing techniques. This paper will highlight the important discoveries of the geometries and the implications the script has on the construction processes. One benefit of using parametric modelling as a component to the manufacturing pipeline is being able to explore several design iterations in the digital realm before ever realizing them in the physical landscape. Furthermore, parametric modelling allows users to control the production documentation and precision needed to manufacture. As a result, the design pipeline presented in this paper seeks to eliminate the construction processes that hinder the physical act of making architecture.

Keywords. Manufacturing process; parametric modelling; 3D printing, plastic casting; mould making.

1. Introduction

The authors began their exploration by questioning how parametric modelling influences the manufacturing process. During this exploration an architectural research project named Protocol began to emerge. In this project, the authors investigate how the manufacturing of plastics (casted, extruded, 3D printed

and rotor-moulded) can be incorporated in the design and fabrication of temporary structures. The framework of this structure is developed through a parametric script which manifests itself through the input of points. These points were studied in terms of the connectivity and relationships to one another, resulting in an architectural framework that resembles a triangulated pattern. The authors chose to work with triangulated geometries because of the ability to link the input parameters to each other and explore the spatial relationships at the simplest geometric level. The wireframe of the triangulated structure marks the dimensional qualities of each controlling point and its influence on the designed space.

Once the digital design of the structure was nearing completion, it was important to investigate the materiality and construction process of the physical creation. Rapid prototyping was used to 3D print the artefacts in ABS plastic. These artefacts would be combined with aluminium, extruded plastic, and other traditional building materials to make up the structure. 3D printing was used not only for its precision but also for developing mother moulds which would be used to simulate mass manufacturing processes.

2. Project development

Protocol manipulates the built environment from the processing of raw data, series of controlling points, in order to reveal the relationship of structural points to one another. A digital model (Figure 1) was generated from a parametric *Grasshopper* script that accepts points as the input values and manifests super connected hubs that allow for the emergence of a structure. The geometry of this design is a lightweight rigid structure that is constructed from interlocking components and a series of linear connections rods. The strength is derived from a triangulation of these components which showcases their connection to another. This triangulated pattern allows the design to transmit tension and compression along the length of each strut, thus allowing space to emerge from the manipulation of connecting points and resemble the tectonic qualities of a space frame (Ahmeti, 2007).

This lightweight rigid structure is connected through customized fabrication components that are controlled by the script. The input parameters that control these components are linked to those needed in the manufacturing process – outer diameters of rods, wall thickness, and shrinkage of material. These printed joints take the place of typical bolt or on site welded connections. The structure was designed to allow for mass production of components and the ability to assemble as a kit of parts. Ultimately, the aim is moving beyond the typical construction processes.

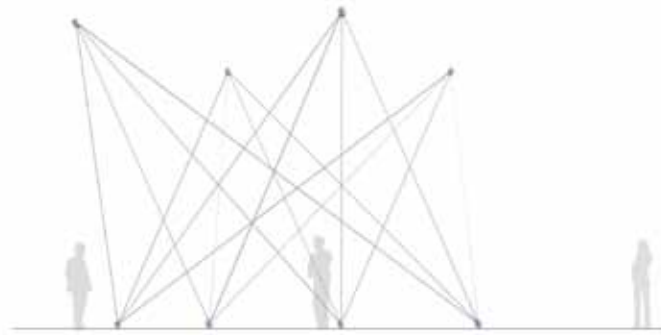


Figure 1: Protocol structure framework without skin

The design was viewed as a way to introduce an adaptive structure, which is digitally fabricated and mass manufactured, into various contexts. Individuals can interact with the space, which does not hold a singular pattern, in the virtual realm and realize the complex connection joints through 3D printing. This is largely made possible because of the integration of parametric elements into the design and manufacturing of the individual components that make up the structure. Rapid prototyping allows the individual to deviate from the typical grid patterns, such as the standard concrete column and space frame layout, to more irregular patterns that have been considered too complex, costly and time consuming to manufacture in the past.

2.1. THEORETICAL FRAMEWORK

Galloway (2004) described the term “protocol” as “a language that regulates flow, directs netspace, codes relationships, and connects life-forms. [...] Protocol is always a second order process; it governs the architecture of the architecture of objects.” Furthermore, Burke (2007) describes the term of “protocols” as “formal constructs that provide the vitality to network logistics, yet they also identify a territory of control points, super-connected hubs of potential leverage within a design context where information is exchanged and regulated.” The design of a protocol is centred on a dynamic network that explores the relationships of one point in space to another (Figure 2). The formal rules that control the points within the design are described by the Grasshopper definition that allows the points to be assigned anywhere within virtual space. Each pair of joints defines the linear roads and drives the visual relationships and allow for a rigid geometry to emerge. It is the introduction of manufacturing parameters into the parametric model that controls the 3D printed joints and final construction of the space.

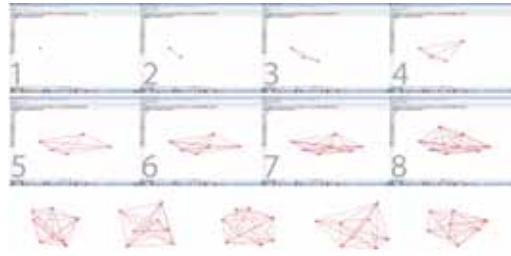


Figure 2: Grasshopper definition and parametric control of fabrication parameters

3. Industrial manufacturing in architecture

Architects are beginning to realize the potential of industrial manufacturing as it relates to the construction processes typically associated with the act of making architecture. The exploration of industrial manufacturing in architectural practice has recently been explored in form making and material processes through digital fabrication. Enormous potential exists in advancing architects' understanding of the ways in which industrial manufacturing drives a design's technological advancement, aesthetics, and user experience. Also, the use of digital and parametric modelling exemplifies the relationship between the informing process of the digital realm and physical manufacturing.

This research not only seeks to incorporate industrial manufacturing in the realization of the built environment, but also showcases techniques that challenge the scalability permitted by current industrial machining processes. To that end, the authors developed and prototyped a full-scale, temporary, lightweight, rigid structure (minimum material, minimum energy and maximum performance) by producing and assembling small scale architectural components in combination with local building materials and construction methods. In order to produce the artifacts for the design, the authors looked to combine several non-AEC techniques utilized in industrial manufacturing, such as mould making from FDM models and casting artifacts, rotor-moulding, and plastic extrusion. This project investigated how to use the automated processes of industrial manufacturing in order to produce large quantities of architectural components in an efficient way. The result of this process is an architectural artefact that can be used as the framework for a temporary structural system within various conditions.

4. Control of parametric design

Once all of the linear paths and joints have been defined in digital space, the design can be considered a structural frame that achieves multidirectional

spans and manipulate the built environment to provide structural strength. This computational design takes each of the controlling points, per parameter, and draws visual connections that make up the static built environment. Each linear path or connecting rod needs to be supported by some artefact. This is where the authors wrote a script to design various multi-connecting joints. The connection joint design is a simple sphere that branches off to receive the connecting rods that span point to point. These super connectors are defined by parameters that are determined by the needs of mass manufacturing such as outside diameter of a rod, material shrinkage, minimum wall thickness for strength, and length of support compared to weight, and length of connecting rod. Removing one of the connection artifacts from the design causes the frame to lose the appropriate amount of structural displacement and may cause the entire structure to fail. Hence for these parameters, the Grasshopper definition outputs the geometry needed for production.

The script was written so the connection joints are self-correcting in terms of the branching elements rotation and angular alignment along the sphere. This allows for the connecting rods to be aligned with each other in the appropriate geometrical pattern. The authors have the ability to quickly assess multiple organizing datasets at a fairly rapid pace. This can be helpful in terms of selecting a structural pattern that may optimize the space and realize the same design ideologies in any context. Also, the parametric model outputs the appropriate documentation needed to 3D print connection joints, making it possible to manufacture multiple iterations or spaces with ease.

4.1. PARAMETRIC CONTROL OF FABRICATION

The input parameters of the parametric model not only defined the design of the architectural connection but also the documentation needed for fabrication technologies. One set of parameters in the model was adjusted to the tolerances that are needed for the 3D printer. The precise nature of digital fabrication machines cannot be assumed and must be tested on a per situation level. For example, in order to prevent weak spots in an architectural artefact it was important to know the wall thickness according to the minimum tolerances of the 3D printer. These types of tolerance tests have too many variables that need to be considered and often take hours to make changes to digital models after testing. However, in a parametric model these tolerances were adjusted through a sliding scale that measured to the hundred thousand, giving us the precision that was needed for manufacturing. Furthermore, parametric parameters controlled wall thickness, length of accepting joints, scale of artefact, and cut length of linear extruded lengths (Figure 3).

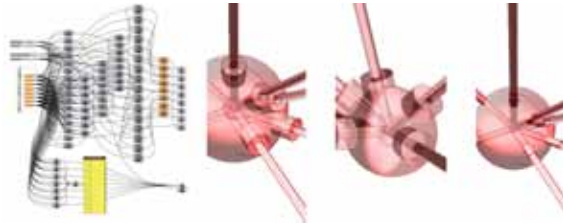


Figure 3: Plastic extrusion process

One of the most important fabrication controls was the outside diameter of the connection length. This controlling input had to be done after the manufacturing of the connections lengths, in order to assure that the length tightly fit and was held in place once assembled. A scalar factor was built into the script to account for the specified manufacture shrinkage of the chosen materials. This important parameter allowed for variable change in the extrusion of connection lengths and the casting of each connection artefact. In realizing that fabrication informs the form, Moussavi (2009) explains “the differences between forms are a product of the complex interactions between material systems (virtual forms) and external materials (the environment).” Here the environment is the product of the manufacturing process. By developing a parametric model designers are not only controlling the fabrication needs but also creating a non-linear workflow that recognizes the importance of how the manufacturing process greatly influences the initial design phase.

Once virtually defined, the connection artifacts underwent a manually performed analysis phase, where the authors addressed complications in the chosen manufacturing technique. If complications were found the parametric model was revisited and manipulated in order to produce a form or surface that is capable of being manufactured. By simulating the process digitally, the authors were able to estimate the time and cost before ever having to engage in the act of making. As a result, the optimized making process directly influenced the parametric model and the aesthetics of the final outcome.

By using parametric modelling to assist in the fabrication process, the designers can create a “highly complex hierarchy of interdependences allowing iterative refinement, i.e. the dimensional fine-tuning of the project in all stages of its development, from conceptual design to construction” (Kolarevic, 2003). As the project in this article demonstrates, the limitation of a machine and capability of materials have to be tested to move from digital to physical modelling. The non-linear nature of parametric modelling demands the designers to be aware these constraints and integrate these factors in the parametric model from the start (Anderson, 2010).

4.2 CHOOSING 3D PRINTING AND MOULD MAKING

The designed connection artifacts are considered complex geometry that is relevantly hard to manifest in the physical world. However, with the use of fused deposition modelling (FDM) and generative scripting in Grasshopper, the authors were able to generate a physical model that represents a static iteration of *Protocol*. The connection joints can be 3D printed and have a precision to them that is very hard to manifest by hand while obtaining tolerances needed to hold the connection rods in place and in the proper rotational direction (Figure 4).



Figure 4: Mould making and casting process

Materiality is able to be explored by taking the 3D printed artifacts and utilize a two part mould making process that generates a mother mould for each of the connection joints. The positive image mould can be created out of wax and used in a lost wax casting of metals, glass and other castable materials. Also, a silicon mother mould can also be used to cast resins or plastics. By simulating the manufacturing process the same precision needed is maintained and the ability to produce artifacts in less time is achieved.

5. Exploration of industrial manufacturing

5.1 INTEGRATION OF PLASTIC EXTRUSION

Plastic extrusion was utilized in the project as a means to mass manufacture tubes which can act as the spanning lengths between connection joints (Figure 5). Plastic extrusion takes raw material into a hopper for drying. Once the material is dry, it is then released into the extruder and pushed through a heated cylinder by a steel screw. The temperature is digitally controlled in order to maintain a constant viscosity of the plastic. At the end of the screw, the material is forced through a die that is within thousands of an inch to the desired profile. The die controls the wall thickness, scale, and tolerances of the final product. The plastic then runs through a vacuum tank where the tube is blown to the proper outer diameter while keeping a constant wall thickness. The vacuum also cools material down and allows the form to hold its shape

as it continues down the production line. At the end of the production line the material is cut into a respective length.



Figure 5: Temporary shelter using connection joint and industrial manufacturing

The extrusion process is able to hold tolerances over an extended period of run time, allowing this process to be constant and inform the parametric model for the production of the connection joints. The authors realized the possibility of plastic extrusion as a means to develop an integrated project delivery between the designer, manufacture, and user. In this process, the quantifiable feature of material property must be added into the parametric network. The script is written to take the outside diameters of the tube and process it through a scaling factor, which is determined by a plastic engineer, of material shrinkage according to its length. The important principles of how material properties affect the design and fabrication process have been exploited by Jenny Sabin. Sabin (2008) explains how a new model of design is realized as “sets of relationships are defined by a blueprint of instructions or algorithms that are then altered and informed through program and especially environment, at all scales.” The authors utilized a parametric design platform as a way of controlling the material properties within the plastic extrusion. As a result the extruded plastic processes and material properties directly influence the parametric script which outputs a scaled factor and is used to determine the accepting diameters of the connection joints. This automated process is only possible because of the manufacturing processes being added as a controlling parameter in the parametric script.

5.2 INTEGRATION OF MOLD MAKING AND CASTING

Mould making and casting techniques were simulated with the intent of them being able to be mass manufactured (Figure 6). The 3D printed connection joints were used as the initial form in developing a two-part mother mould. The mother mould was poured from a silicon rubber that has a high durability and life expectancy. Because the 3D printed connection joints have a series of undercuts within the design it was important to use Dragon Skin silicon rubber

or similar silicon product for its durable nature and high levels of elasticity. The process of making a two part mould is a common practice in industrial manufacturing processes. This type of mould can be used to produce hundreds of casted parts without losing quality in the final product.



Figure 6: Mould making and casting process

Once the mother mould was developed the researchers casted a crystal clear resin mixture in order to simulate manufacturing process. The resin connection joints are very strong and hold the same precision as the 3D printed parts, making it easy to use the same plastic extruded tubes as the linear connections between the connection joints. It is a workflow that is ultimately influenced by the parametric modelling and its ability to develop models that have the precision need to fabricate such structures.

6. Conclusion

Parametric modelling has shown to have substantial benefits when used as a design and production drawing generator for digital fabrication. One benefit is that the designer has the ability to experiment with numerous design and tooling possibilities. Parametric modelling can also produce material take-offs and cutting diagrams for production, CNC tool-paths, assembly labels, and stereo lithograph files used in three dimensional printing. This project shows how a parametric model was not only used to generate forms but also used as a tool to assist the pre-making processes needed for fabrication.

This investigation of the manufacturing process has extended into projects such as “Folded House” (Tang and Yang, 2008). The temporary structure can be used as relief shelters in areas affected by natural disasters, as portable gathering pavilions, and many other diverse applications (Figure 7). This approach not only allows for easy assembly and disassembly but also the ability to reconfigure into several iterations. The design allows for variable changes in the way we populate our physical landscape and take advantage of industrial manufacturing in producing multiple scenarios. Through this work, the authors have further explored the current research on industrial manufacturing and the use of parametric modelling to assist in the fabrication process.

Ultimately, the research will promote and establish a constant relationship between digital design processes and the act of making through industrial manufacturing. This newly formed relationship benefits designers by exposing them to the emerging technologies that can be used in the act of making architecture during the 21st century.



Figure 7: Temporary shelter using connection joint and industrial manufacturing

A new generation of architectural designers can utilize this research as a basis for understanding the potential contributions of the manufacturing industry to the profession of architecture. Interactions between digital and conventional methods promote new ideas and create an environment conducive to collaboration between architecture and industrial manufacturing. The use of parametric modelling to inform the fabrication and manufacturing process was considered as “psychological change rather than just another form seeking method.” (Tang and Anderson, 2010). Thus, a new breed of designers begins to emerge, one that capitalizes on manufacturing, economy, and project integration.

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SUPPORTING SHAPE REINTERPRETATION WITH EYE TRACKING

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Abstract. It has been argued that reinterpretation is an essential process in design generation and idea exploration. However, computational design tools, such as computer-aided design systems, offer poor support for shape reinterpretation, and as such are not well suited to ideation in conceptual design. One of the key difficulties in implementing computational systems that support shape reinterpretation is the issue of interface – how can a user intuitively guide a system with respect to their interpretation of a designed shape? In this paper, a software prototype is presented that uses an eye tracking interface to support reinterpretation of shapes according to recognised subshapes. The prototype is based on eye tracking studies, and uses gaze data and user input to restructure designed shapes so that they afford manipulation according to users' interpretations.

Keywords. Eye tracking; shape interpretation; computer-aided design; design generation; design exploration.

1. Introduction

This paper presents a software prototype that uses an eye tracking interface to support the creation and manipulation of designed shapes in the generative and explorative stages of conceptual design.

Conceptual design, in a number of creative professions, involves the creation, exploration, and development of design shape alternatives, and is typically supported using freehand sketches. The ambiguity of sketches

supports the cognitive process of image reinterpretation which is central to effective shape exploration and development (Schön and Wiggins, 1992). Commercially available computational design tools, such as computer-aided design systems, are typically not well suited to conceptual design activities because the support they offer for the reinterpretation of shapes is poor; they are instead typically used during detail design and design definition.

When discussing reinterpretation in design it is important to distinguish between interpretation of the *semantics* of a shape, and interpretation of the *syntax* of a shape (Goldschmidt, 1991). The first is concerned with assignment of meaning and involves cognitive processes that are difficult, if not impossible, to formalise; while the second is concerned with the structure of the geometric elements that define design descriptions. This research is concerned with supporting syntactic interpretation, which is also a vital element of any potential support for semantic interpretation, as discussed in Section 5. The software prototype presented here makes use of emerging eye tracking technologies to support dynamic reinterpretation of designed shapes according to recognised structures, and is based on experimental studies in which the gaze of participants was recorded as they looked at and manipulated shapes. The resulting system is an advancement towards what Saund and Moran (1994, p. 175) view as an ideal system for design exploration, and is intended to

read the user's mind (his visual system in particular) and synchronize with whatever image entities the user happens to perceive as significant.

Eye tracking technology has the potential to substantially reduce the cognitive overhead needed for designers to interface with computational design systems. The prototype presented here is a first imagining of the possibilities, and is intended to allow designers to focus on their design activity, with the software as a tool that supports without disturbing the creative flow.

2. Background

The ability to interpret and reinterpret shape is a fundamental skill in visually creative activities such as conceptual design. It has been observed that, when sketching, designers often produce series of ideas that are, in places, inevitably ambiguous and open to reinterpretation. These design alternatives are explored visually in a search for patterns and associations that lead to new avenues of exploration. Schön and Wiggins (1992) describe this as a 'seeing-moving-seeing' process where seeing a sketch can result in its reinterpretation according to emergent forms or structures, and this in turn informs the development of future sketches. Exploration in this way typically involves the

recognition and transformation of shapes in sketches, such as overall outline shapes or the embedded parts of shapes, so-called ‘subshapes’ (Prats et al, 2009).

Despite the importance of reinterpretation in design exploration, it is not readily afforded by the current generation of computational design tools. For example Goel (1995) and Stones and Cassidy (2010), present comparative studies in which designers undertake conceptual design tasks using either sketching or commercial computational design tools. In both of the studies it was found that participants readily use reinterpretation in their design exploration if sketching, but not when using computational tools. However, Stones and Cassidy observe that reinterpretation did take place cognitively when computational tools were used, although this was not evidenced in the creation of new solutions. They suggest the reason for this is because, when participants were using computational tools, they were looking for accuracy in their design concepts and until a form closely resembled their mental picture they were unable to progress to alternative interpretations. Lawson and Loke (1997) propose a more pragmatic reason and suggest that development of computational design tools has placed too much emphasis on graphical representation techniques. As such the resulting tools are unable to support processes essential to explorative design, including the process of shape reinterpretation.

A key difficulty in supporting shape reinterpretation is the problem of developing an interface that allows the user to specify their current interpretation of a designed shape so that the system can afford the required manipulations. Conventional selection techniques such as pointing, clicking, or encircling shapes with a mouse are not always practical because of ambiguity that arises due to overlapping interpretations. Research into this problem has resulted in a range of approaches that enable the manipulation of designed shapes according to recognised structures. For example, Saund and Moran (1994) present a WYPIWYG (What You Perceive is What You Get) drawing system that enables perceptual interpretations of a digitally sketched shape to be specified and manipulated according to simple pen-based gestures; Gross (2001) presents the ‘Back of an Envelope’ system, a drawing program that uses standard pattern recognition techniques to automate the recognition of emergent subshapes in a digital sketch; Jowers et al (2010) present an approach based on a shape grammar formalism (Stiny, 2006), in which shape replacement rules are applied to identify and manipulate recognised subshapes in a design.

A major limitation to each of these approaches lies in the cognitive overhead needed to interface with the systems. For example, in Saund and

Moran's system, users are required to learn gestures that specify particular interpretations of a shape; in Gross' system users are required to trace over shapes of interest in order to specify their interpretation; in Jowers et al's system users need to define shape replacement rules before shapes can be manipulated. In each of these, additional effort is needed to interact with the system to specify a particular interpretation of a shape and, no matter how small this effort is, it can result in an interruption to the creative flow of the user. A more intuitive, dynamic system, one that better supports a cognitive process of 'seeing-moving-seeing', would offer real benefits in avoiding the need for users to explicitly define their interpretation of designed shapes. To this end, eye tracking technology presents itself as a potential interface for computational design tools.

Previous research has explored the application of eye tracking as an alternative drawing interface, to replace traditional mouse and keyboard input, e.g. Hornof et al (2004). Here, eye tracking is used as an additional interface, augmenting traditional input. In the software prototype, gaze data is used in combination with mouse-input to reveal a user's interpretation of a designed shape at a particular moment in time, and the software responds by affording manipulation of the recognised subshapes.

3. How do users look at shapes?

In order to inform development of the software prototype, a series of eye tracking studies was conducted with the aim to build an understanding of how gaze data can be used to support shape reinterpretation in a computational design tool.

Gaze data, consisting of scan paths and points of visual fixation, can reveal much about how shapes are viewed and interpreted. The studies reported here attempted to identify gaze patterns that could be used to distinguish between shapes that are attended to and those that are simply looked at. Attention to a shape is a necessary process that precedes interpretation (Fu et al, 2006), and is identified by focus on one particular shape in an image, whilst ignoring others that are also present. This act of attending is linked to the act of selective looking but not necessarily to the act of recognising.

In the studies, participants completed tasks in which they were encouraged to employ different visual strategies, including free-viewing, shape search, and attention to specified shapes. For example, in the search tasks, participants were asked to search images composed of shape primitives for specified shapes, and to vocalise when they had found the target shape. An example of the images presented to the participants is given in Figure 1, along with an example of the gaze data collected. Here, the participant was asked to find the

arrow highlighted in Figure 1a, a task made more difficult due to the necessity to undertake a figure-ground reversal.

During the studies, gaze data was collected using a Tobii X120 – a non-intrusive eye tracker that allows for some head movement. Verbal data was also collected facilitating a comparison between gaze patterns that relate to seeing shapes and gaze patterns that relate to attending to shapes. Analysis of the data identified patterns of viewing consistent with attending to shapes. It was found that, when participants were seeing shapes without attending to them, the scan paths followed no pattern of note but tended to be loosely concentrated around the centre of the image, with the majority of visual fixations taking place inside individual shape primitives, as illustrated in Figure 1b. However, a dominant pattern emerged when shapes were attended to, with a majority of scan paths and fixations concentrated around the centre of gravity of the attended shape, as illustrated in Figure 1c. This confirms the findings of Vishwanath and Kowler (2003), who report that participants attending to simple shapes naturally fixate on the centres of gravity.

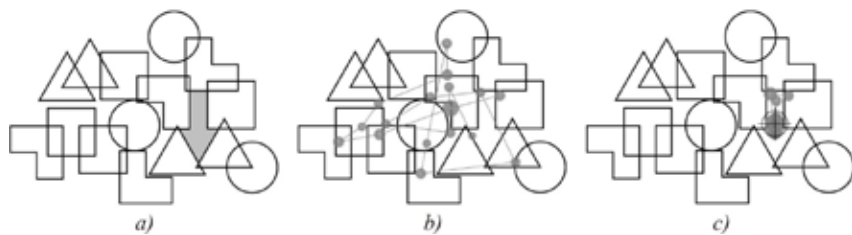


Figure 1 – Stimuli and corresponding data from a shape search task

The studies also explored how gaze data reflects interpretation of ambiguous shapes. This involved tasks in which participants were asked to fixate on specified subshapes of an ambiguous shape. For example, in one task participants were shown the five-point star in Figure 2, and were asked to attend to specified subshapes, examples of which are illustrated in Figure 2a. The aim of these tasks was to determine whether or not it is possible to infer a viewer's interpretation of an ambiguous shape by comparing their visual fixations with the positions of the centres of gravity of potential subshapes of the shape. As with the shape primitives, it was found that when participants were seeing a shape without attending to any particular subshape the gaze data had no pattern of note. But, a dominant pattern emerged when subshapes were attended to, with a majority of scan paths and fixations concentrated around the centre of gravity of the attended subshape, as illustrated in Figures 2b and c.

However, it was also found that if a shape is composed of subshapes that have centres of gravity that are close together (within a distance of

approximately 50 pixels), then it is not possible to unambiguously determine which of the subshapes is being attended to based purely on gaze data. For example, the gaze data illustrated in Figures 2b and c could not conclusively identify which of the two subshapes the participant was attending to because their centres of gravity are too close. Instead, it is only possible to identify subshapes that were *potentially* attended to.



Figure 2 – Stimuli and corresponding data from a shape interpretation task

4. Supporting shape reinterpretation

The results of the eye tracking studies were used to inform development of a software prototype, implemented using the Tobii Software Development Kit. Key to implementing the prototype was the identification of potential interpretations of a designed shape. Also, there was a need to understand users' interpretation of designed shapes based on potentially ambiguous gaze data and mouse-based input. In this section, these issues are discussed, and the methods used to address them are presented. The resulting software prototype is illustrated with an example showing how the user is able to manipulate subshapes of interest in a designed shape.

4.1 IDENTIFYING POTENTIAL SUBSHAPES

Central to the use of gaze data for determining a user's interpretation of an ambiguous shape is information about the centres of gravity of potential subshapes embedded in the shape. The brute force approach to determining this information is to calculate all possible subshapes and then calculate their centres of gravity. For example, the subshapes can be calculated combinatorially by considering sets of lines that are embedded in the shape. However, this approach is computationally very expensive, and will result in consideration of subshapes that are very unlikely to be considered by a designer manipulating the shape, e.g. subshapes composed of single lines.

The approach used here is more selective, and is similar to that implemented by Gross (2001). In the software prototype, users are able to build up a library of shapes that they find interesting. The library is populated in two ways:

firstly, any shape that the user explicitly draws is added to the library; secondly, the user can trace over any interesting emergent subshapes and so add them to the library. Shapes in the library are compared to the current designed shape using a method of subshape detection, as described by Trescak et al (2009), and every similar subshape that is detected is made available for selection by the user.

4.2 RESOLVING AMBIGUITY IN SUBSHAPE SELECTION

As discussed in Section 2, when manipulating recognised subshapes in a designed shape, mouse-based methods of selection are not always practical, especially if different interpretations of the shape overlap. This is because the geometric elements that are used to construct shapes can be shared by different interpretations, as illustrated in Figure 3a, where mouse-based selection cannot unambiguously determine whether the user is selecting the triangle or the square. Input from an eye tracker can be used to determine which subshape the user is attending to at a particular moment but, as discussed in the previous section, if subshapes have centres of gravity that are close to each other then it is not possible to unambiguously determine which specific subshape is being attended to. This is illustrated in Figure 3b, where gaze data cannot unambiguously determine if the user is attending to the outer or the inner square, because they share a centre of gravity.

A combination of the two methods of input can serve to cancel out much of the ambiguity that can arise. In combination, gaze data can resolve the ambiguity in mouse-based input, and mouse-based input can resolve the ambiguity in data from an eye tracker. This is illustrated in Figure 3c where the combination of the two methods means that the user can unambiguously select and manipulate the subshape of interest, the inner square.

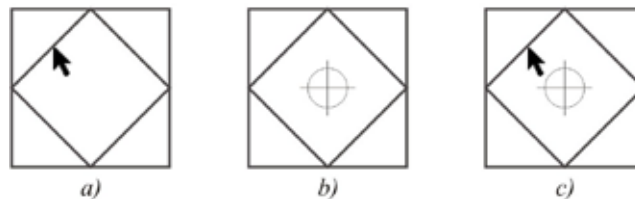


Figure 3 – Ambiguity in shape interpretation

4.3 SUPPORTING MANIPULATION OF RECOGNISED SUBSHAPES

These methods of identifying potential subshapes and resolving ambiguity in subshape selection have been implemented in a software prototype, the

user-interface of which is illustrated in Figure 4. The user-interface consists of a large drawing area (on the left hand side), a shape library (on the right hand side), and various eye tracking tools, such as the dialog in the bottom right corner that reports the current status of the gaze data being recorded. In the software, shapes are defined as sets of line segments, and subshapes are defined according to subsets of these. Users can manipulate constructed shapes by translating the end points of individual line segments, or by selecting and translating defined subshapes.

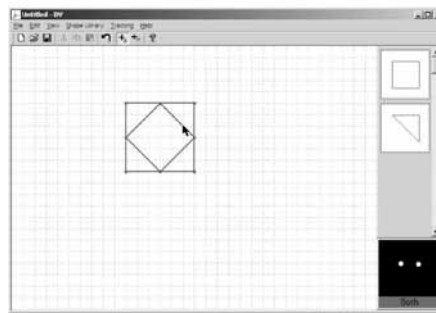


Figure 4 – The software prototype

Initially, subshapes are defined according to how a shape is constructed but as shape exploration proceeds, and the shape library is populated, the constructed shape can be reinterpreted according to recognised subshapes, which can then be selected and manipulated. For example, in Figure 4 the shape was constructed as two squares, and a square and a triangle have been added to the shape library. Accordingly, in Figure 5, this designed shape is manipulated by translating recognised square and triangle subshapes.

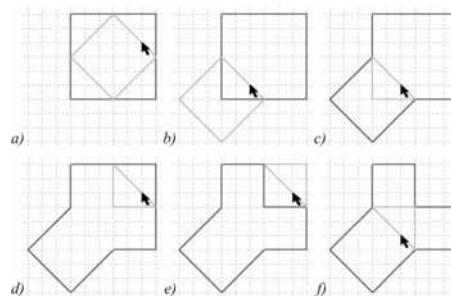


Figure 5 – Manipulating subshapes of interest using the software prototype

Note that the mouse-based input remains constant throughout the example, with the user always selecting the same line segment. However, because the

user is attending to different subshapes according to different interpretations of the designed shape, it is possible to manipulate different parts of the shape. This is clearly illustrated by comparing Figure 5d and 5e, where the user attends to different triangles and consequently is able to select and manipulate those triangles, in turn.

At each stage of the explorative process the centres of gravity of the detected subshapes are used in combination with mouse-input and gaze data to determine the current interpretation of the designed shape – if a user is attending to a subshape that is similar to a shape in the library, and if that subshape is selected using mouse-input, then it is made available for manipulation through the application of an identity shape rule (Stiny 1996). Such rules are of the form $A \rightarrow A$, where A is a recognised subshape, and application to a designed shape S , results in the shape $(S - A) + A$. Identity rule application serves to restructure the designed shape S so that the recognised subshape A is defined and is available for manipulation.

5. Discussion

This research is an exploration of the two-way conversation between the designer and the design representation – the maker and the made. Schön (1988) argues that design does not conform to an objectivist philosophy, where things are what they are independently of how they are interpreted. Instead, he argues that design is constructionist. Designers construct their knowledge of a design problem as they explore potential solutions. Central to this process are *gestalts*, coherent wholes that are defined by designers' interpretations of the geometric elements that compose design representations. Gestalts enable designers to reason about design problems, and are not fixed. The same set of geometric elements can be reconstructed as many different coherent wholes, and a designer often shifts gestalt during design exploration. The research presented here has explored how a computational design system can support such gestalt shifts, and it has proposed a method for computationally supporting the constructionist philosophy of design.

Gestalts result from semantic interpretations of shapes, involving cognitive processes that are beyond the scope of this research. But, manipulation of a shape according to a particular gestalt is only possible if the structure of the shape, i.e. its syntax, is compatible. Therefore, in order for a computational design tool to support gestalt shifts it is essential that syntactic interpretation of shapes is afforded. Here, syntactic interpretation is supported using an eye tracking interface. The combination of gaze data with traditional user input serves to dispel much of the ambiguity that can arise with respect to the user's intended manipulation of a designed shape. As a result, the software prototype

is able to support reinterpretation of designed shapes according to alternative sets of embedded geometric elements that reflect the user's current perception of the shape.

It is a difficult task to develop a computational system that can recognise different interpretations of shapes, and the solution presented here uses a compromise whereby the users themselves specify potential interpretations based on recognised subshapes, but in a manner that is as non-intrusive as possible. It is anticipated that this will allow designers to focus on their design activity, with the design software as a tool that supports without disturbing the creative flow.

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GENERATIVE AND PARAMETRIC DESIGN III

11. Affordable, performative and responsive: Designing affordable responsive architectural prototypes through physical and digital modelling 113
M. Kamil Sharaidin and Flora Dilys Salim
12. Searching generative methods based on building environments 123
Biao Li and Rong Li
13. Graph visualization in computer-aided design: An exploration of alternative representations for GenerativeComponents™ Symbolic View 133
Karine Kozlova, Roham M. Sheikholeslami, Lyn Bartram and Robert F. Woodbury
14. Designing elastic transformable structures: Towards soft responsive architecture 143
Chin Koi Khoo and Flora Dilys Salim

AFFORDABLE, PERFORMATIVE, AND RESPONSIVE

Designing affordable responsive architectural prototypes through physical and digital modelling

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Abstract. The significance of this research lies in the investigation of agglomerating issues of affordability in responsive architecture to achieve long term performative and cost-saving benefits. Conventionally, performance analysis of responsive design is evaluated using simulation of digital model. The inaccuracy of most building performance simulation leads to a huge prediction error in the actual building performance, which yields miscalculation in the building operational cost. This paper proposes a novel method for delivering a cost benefit analysis for responsive design. Two different strategies are explored in parallel. Firstly, hands-on approach through fabrication of physical models which directly associated to digital models, whereby the fabrication and operational costs of the physical prototypes are measured and monitored. Secondly, qualitative approach through cost benefit analysis of real world building projects which employ responsive architectural components.

Keywords. Responsive design; affordability; performative design; low-tech.

1. Background

Recently, there is an increasing interest in designing responsive architecture to meet aesthetics and performative design goals. Creating envelopes and objects that can physically reconfigure themselves to changing needs is one of the attempts to improve building performance (Fox, 2007). However, the issue on affordability has always becomes a major hindrance in translating this idea

into built projects as new technology and mechanical system involve high cost. This is supported by Haque who believed that the complexity, logistic and costs have prevented their prototype research (2007).

On the hand, responsive architecture often does not require very sophisticated equipment to develop a truly interesting project, for instance, by adapting relatively simple technology, utilising available materials and mechanical system. Therefore, the solution lies in what is called 'open sources architecture', combining reusability and low tech. Hence, in implementing responsive architecture, it is suggested that new media artist and architect practise precision and accuracy that scientist do in order to explore the poetries of interaction (Haque, 2007).

Looking into a wider context at the implementation stage, the successful of responsive architecture lies in fulfilling the environmental criteria and cost constraints. In highlighting this dilemma, the need for researches and practical solutions for an affordable technique should be developed and explored to address today's challenges in generating efficient building (Fox, 2007).

Hence, this project scrutinizes the issues of affordability in designing responsive design performance, by utilising parametric design and prototype model strategies. In obtaining accurate data for energy usage and performance, parallel explorations of digital modelling and hands-on physical prototyping are implemented using affordable electronic devices such as *Arduino* processing boards. The physical model obtains input from the environment whilst the digital model responds to the input. Subsequently, this data is evaluated using cost benefit analysis and repeated for the other models. Based on this approach, series of responsive models are fabricated by integrating low-tech mechanical system and low-cost materials. Cost evaluations are conducted on the energy usage, low tech application, materials and design performance from the output of both models to identify the optimum behaviour and to be extended for experiment towards actual buildings.

2. Design problems

Though existing building simulation software can be used to study building performance, costs and energy consumption, yet they are limited to static building with no responsive elements. Previous studies have shown that digital simulation outcome at design stage do not contribute to enhance building performance after been occupied. This is due to inaccuracy of data from digital simulation experiments at early design stages (Leaman, 2006). Alternatively, physical prototypes simulation is suggested to overcome the above problem. Though the prototypes may represent the movement in responsive buildings, for instance, tracking the sun movement, yet they cannot be associated with

the energy consumption and building performance.

Therefore, the combination of these two simulations would be useful in responsive design constructions study, where the challenges and limitations to create affordable and performative responsive design are the pillars of this research. Realising the lack of study and in the absence of integrated digital and physical modelling has been the key motivation in exploring this kind of experiments to produce affordable responsive architecture.

It is worth to mention that the issue of costs has always be the key issue in any responsive or kinetic architecture. Yet, novelty of the subject and insufficiency of evidences have provided no concrete answers on the affordability of responsive design (Angeliki, 2010). Usually, market demand shows that products will be at higher costs at the beginning of market released, but may drop at very low rates when become vastly available to the public (Angeliki, 2010). However, in relation to building performance and efficiency, this principle may not apply in analysing the responsive design cost, as it involves long term building cycle costs i.e. energy and maintenance costs. For that reason, this paper will experiment on how affordable responsive architecture can be evaluated and analysed before being build. The integration between digital and physical data is important to produce affordable responsive designs which are parallel to the actual building performance.

3. The design process

This design process involved data evaluation from digital and physical models. Figure 1 shows the experimental process of evaluating both digital and physical prototypes from the existing responsive building elements, focusing on the affordability of responsive design. Since this process involved hand-on experiment, preliminary problems of responsive design were analysed and identified for further evaluation and improvement through various solutions.

Designing prototypes are basically a thinking activity. The proposed prototype models – in this case building design process – is a kind of framework which is in accordance with the nature of thinking activities with no sequential process. Hence, the development on the solution to a design problem is a responsive search process, driven by insight and creative leaps within the framework of affordable responsive architecture. The framework is meant to support the exploration and clarification of the problem as well as to extend the solution for affordable responsive architecture by various means such as, development of scenarios and strategic values in developing an innovative approach towards the design process of responsive building. The creation of a building (conception, design and development) is a process of crystallisation from all directions, starting from a conceptual centre outwards.

Through this process, based on Figure 2, the first stage looked into the application of mechanical system, followed by how the system can be replaced by sensor and actuator whilst the last stage considered the integration of low tech material and method for energy reduction with better performance.

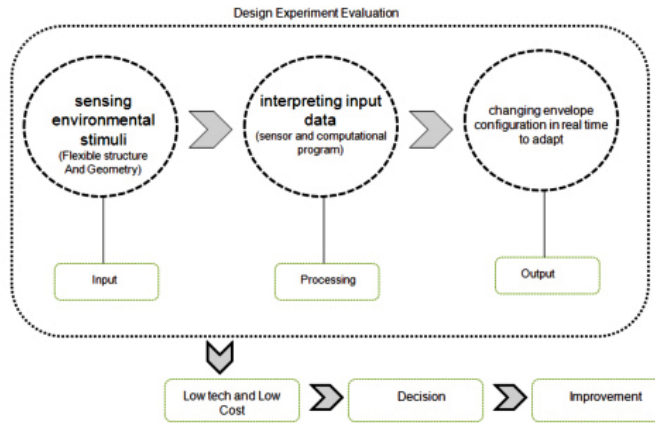


Figure 1. Design experiment evaluation

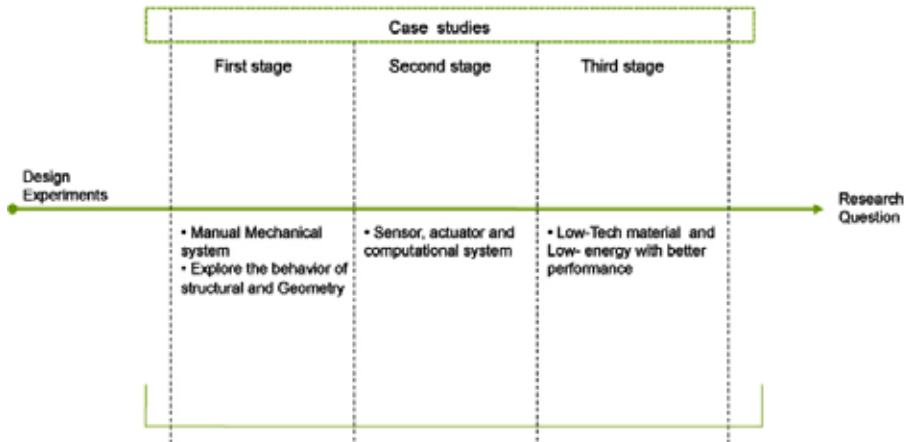


Figure 2. Evaluation on affordability and performance

3.1 STAGE 1: DESIGNING AND EXPERIMENTING THE MODEL MANUALLY

The first stage in responsive prototype model construction looked on how the responsive model operated and responded to specific environmental condition.

The model was first constructed using digital modelling (Rhino and Grasshopper) where problems and issues were identified in relation to

responsive mechanism. Then, the 3D modelling was physically constructed using available materials with very simple method. Cost and time for constructing the model were evaluated throughout the process.

3.2 STAGE 2: PROTOTYPING WITH PERFORMANCE AND MECHANICAL BEHAVIOUR

In the next stage, *Arduino* boards, motor, sensor, actuator and computational system were integrated into the prototype model to experiment the technologies applied in responsive model and to improve the prototype performance. The process of adapting this low tech application were re-evaluate and re-design to get the possible optimum performance and considering its application to the real building situation.

3.3 STAGE 3: EXPERIMENTING WITH OTHER SMART MATERIAL AND ENERGY

The third stage looked into replacing the technical and computer application with low tech and smart materials. The objective of this process is to find an alternative solution for the model to operate in accordance with the same intention and performance of the mechanical system. This process may provide affordable installation, operational and energy costs used by the model. This idea and process can be projected to the actual building to evaluate the outcome and performance of the responsive facade before applying it to the real building design.

In the past, most of the responsive system involved very high tech mechanical system. Hence, it is time to look for different approaches in operating responsive design through integration of smart and low-tech materials (Fox, 2007). Since the process of constructing responsive prototypes deal with cost and prototypes performance, the solution should be explored in the context of smart material and low tech application which are suitable for responsive facade design. The materials such as Smart memory alloy, ETFE and Paraffin wax can be adopted into responsive design façade to replace the mechanical system in producing affordable and effective responsive design. This material are quite expensive in the market at the moment however, as this materials slowly adapted to the building construction the material will be affordable.

4. Design and Development of Responsive Prototypes

4.1 PROTOTYPE MODEL 01



Figure 3. Prototype model 1

The model was constructed by considering possible behaviours of kinetic facades and envelopes which applied mechanical system. The behaviours were tested using manual mechanical system and problems were identified and resolved by simplifying the mechanical system work on the prototype model. Based on Figure 3, Prototype 1 used two panels to move thirty panels in different positions; up and down which create different form and behaviours. The panel relies on different position of planes which are located in different degrees. These panels can be adjusted and reconfigured to avoid cost increase in redesigning the responsive facade. This panel can be adapted into real building as re-adjustable shading devices.

4.2 PROTOTYPE 2



Figure 4. Prototype model 2

The responsive prototype model in Figure 4 was developed based on available materials using straws, bamboo sticks, mdf boards and rubber band while the model behaviour was develop based on open and closed panel. The flexibility of each panel depends on the opening degree in every square panel. The model can be operated by using rotation at the back of the prototypes.

At the first stage, the prototypes were developed and tested using manual system to determine whether the prototype behaviour is responding properly and effectively. The main design goal of the prototype was to achieve high efficiency and low operational cost in real-world buildings.

4.3 PROTOTYPE 3



Figure 5. Prototype model 3

The prototype in Figure 5 and 6 were constructed using paper and stapled clips. Based on simple behaviour of the façade system, *Arduino* board and light sensor were used for the opening and closing. For instance, *Arduino* and light sensor in Figure 6 can be programmed and adjusted to suit user requirement or the intended behaviour. The main issue of developing this model is low energy supplied to make the prototypes more responsive and effective.



Figure 6. Prototype model 3

5. Preliminary outcome

Considering the possibilities, limitations and nature of the problem, the first approach is to create a responsive prototype for responsive facade which is in parallel to the affordability and building performance. Since the sustainability issues are essential to the building performance, the preliminary investigation of responsive prototypes model shows that the mechanical system and the application of right material are very crucial in developing responsive facade design.

Table 1 demonstrated that simple construction may produce more efficient and effective responsive models with lower installation cost and minimum assembly time. The model creation takes longer time since it involves designing around the actual problems of responsive architecture design. The workability of prototype was experimented digitally in Rhino and Grasshopper before physical construction. The physical installation of responsive affordable prototype deals with similar type of real construction of responsive design. This may provide a real idea on how the affordability and performance of responsive architecture can be realised. From the data collection and analysis, it is suggested that the integration of digital and physical models offer a quick turnaround in order to test, manufacture and market our idea as well as produce good quality of responsive prototypes from computed generated data in relation to hours, instead of week. Besides, prototyping our design idea can be tested and refined quickly and economically resulting in tremendous reduction in development time costs and enhancement in the final result.

In comparison to the complexity and behaviour between Prototype 1 and 3, the construction of Prototype 1 was more complex than Prototype 3 as the behaviours of responsive elements were almost similar. As the cost of Prototype 3 was lesser than Prototype 1, the experiments showed that in order to create affordable responsive architecture, the early design stage should be simple and practical. From the time and cost point of view, results will vary according to the size, complexity and geometric definition of each prototype. It is difficult to estimate and analyse the accurate model creation method as there are too many iterations associated to modelling prototypes i.e. designing a parametric model, exercising parameters, prototyping material, defining parts and different technologies required in the process. Therefore, the results presented in this paper are best suited for scaled prototype models whereby similar parts are constructed using similar modelling parameters.

This will lead to an affordable responsive prototype whereby this estimation can be projected to the actual responsive building design at the early installation stage for an affordable responsive design.

Table 1. Total cost of prototypes model

	Data preparation (hrs)	Design (hrs)	Model creation /assembly time and cost	Material cost (Aud)	Post prototype operational cost(Aud)	Finish cost (Aud)	Total cost of rapid prototyping (Aud)
Prototype1	2	5	40+6	10	5	4	25
Prototype2	1	2	10+7	8	4	3	21
Prototype3	1	2	12+7	6	2	3	18
Prototype4	1	1	9+7	6	2	2	17

Besides, Fox highlighted that as most of the smart system has been explored in engineering, aerospace and agriculture area, the time has come for the application of smart material and low-tech technology in architecture, specifically to the responsive design facade to create solution for the building performance and affordability issues (2007).

6. Conclusion and future work

In designing responsive prototypes model, there are a few requirements that should be considered:

- Satisfied technical criteria of designing responsive design
- It is impossible to reach one best solution
- Always considering double loop learning and adaptation
- Creativity and experiment will play an important role in innovation approach.

The proposed responsive prototypical model may to a certain extent are idealistic and risky but at the same time provide solutions to all initially set challenges—such as facilitate the development of responsive architecture, complex interactive environments with the prototypes, as well as the issue of affordability and building efficiency for integrated design and prototyping in dynamic architectural systems.

It is acknowledged that the lack of standards and no predefined method for simulation of responsive prototypes models may (and arguably, should) lead to larger inconsistencies among different future implementations developed under the experimentation of responsive architecture. However, to date, most of the experimental projects in the domain of responsive design do not conform to any common models. Thus, providing a framework without any substantial constraint to freedom of creative exploration seems to be the only solution to allow further development of experimental responsive models, while providing a platform for interoperability and reuse of components, sub-models and plug-ins across projects when desired. To further facilitate this experiment, the exploration of affordable responsive model should be tested as one to one scale model integrated with integration with digital model and

apply towards the actual building facades. This method of experiment is one of the effective ways to identify and to analyse the affordability and performance of responsive design facade. The exploration and adaptation of smart material and low-tech system are significance in ensuring the responsive design facade working effectively and efficiently at the same time affordable.

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SEARCHING GENERATIVE METHODS BASED ON BUILDING ENVIRONMENTS

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Abstract. Architectural contexts present both resources and restrictions from local spatial environment, such as factors of sunlight, landscape, line of sight, terrain and etc. They play important roles in architectural design. Following the traditional methods, it takes the architects lots of time to analyse the relative relationships. This paper takes terrain and sunlight into consideration to illustrate how to employ generative methods at the early stage of architectural design.

Keywords. Terrain context; sunlight; multi-agent; genetic algorithm, evolve.

Applying tremendous amount of architectural elements to the set of agents and materializing their characteristics to dynamic motion, multi-agent generative models employed in architecture require architects to survey kinds of architectural rules and elements as mutually cooperative agent systems. Moreover, the approach should be translated from angle of architects-oriented to angle of the architecture-oriented. By means of theoretical investigation and case studies of architectural environmental contexts for harmonizing future environments of new architectural schemes, any prototypes and parameters for computer programming will be extracted, synthesized and evolved via *Simple Genetic Algorithms* to both enhancing efficiency of architectural design and promoting people's environmental awareness. Any tools developed in our toolkits are specific to the techniques for architectural design during the early stages, and the two factors, terrain and solar, are selected as examples in this paper to demonstrate the process.

1. Generating terrain based on a picture

All terrain information, such as properties of altitude, geometry, water, and spatial dimensions of lands, must be set as initial conditions for evolving of computer program. Many tools developed could be supportive in an alternative way, for example, *GIS* can support the terrain generation. However, this kind of software developed by other computer languages, such as *C++*, can't be packaged into our *Java* based developing generative tools. More importantly, the files input from *GIS* contain too much information than we need, and can't be employed to loop the evolutionary process of *Genetic Algorithm*. A simple but efficient new algorithm should be applied for generating different kinds of site terrain.

Some computer languages and file formats, such as *Extensible Markup Language* (XML) and file type of “*.dxf”, are competent for implementing datum of a predefined site as simple as in figure 1-left for example, all dots' coordinates of the “key turn” in the site can be input one by one or predefined by XML. However, while dealing with the site of the future real estate projects, it is previously unpredictable whether the site will be as simple as figure 1-left or complicated as that of figure 1-right, and it is a tedious job for users to input datum of a complicated site even it's only a description of 2-dimensions, let alone any other 3-dimensional information of altitude (coordinates of *z* added). One possibility based on pixel analysis which presented as follows may solve the problem of spatial data input and editing, meanwhile, the output keeps different kinds of properties, such as, land, grass, river or mountains and etc.

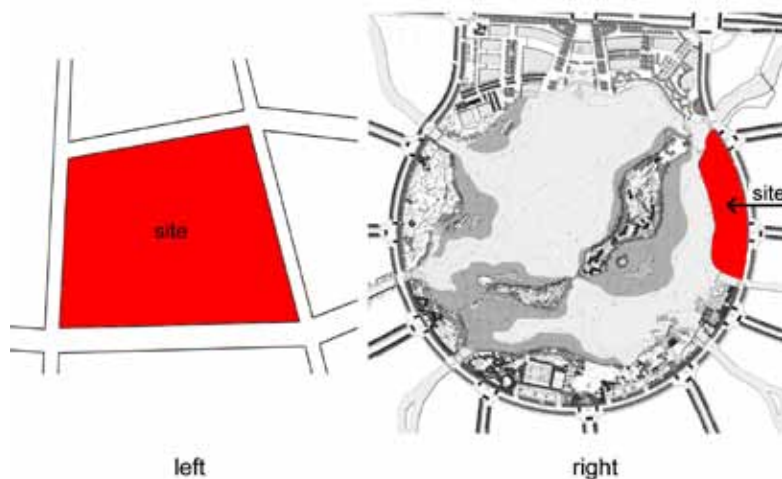


Figure 1. Simple and complicated datum for sites and their environments

The first step of extracting the datum of a site is to translate the surrounding spatial context to a picture filled with series of pure colours presented in figure 2 as an example. Colours can be parameterized according to their content of Red, Green and Blue (RGB). On one hand, each part of architectural environmental context maintains characteristic of “pure colour”; but on the other hand, it keeps any other specific information, for example, the green colour denotes spaces of green land, which whose “G” parameter is 255, but meanwhile, the parameter of “R” and “B” denote its altitude. As presented parameters of “G” in figure 2 on top-right, values of a, b, c and d are 255, but their “R” and “B” are all different, which the values of “R” and “B” are mapped for their altitudinal datum.

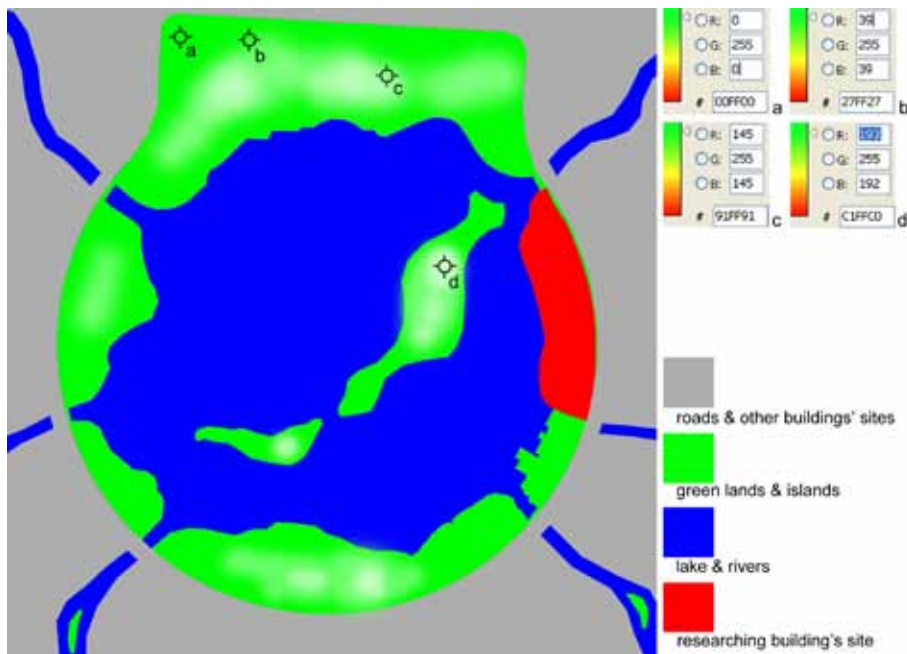


Figure 2. Different colours denote various data

Employing the technique of pixel-based analysis, the whole datum of the 3D terrain in figure 3 will be generated from the above picture. Different resolution of meshes can be generated according to defined parameters. One noteworthy point is that the generated achievement of the site is divided according to predefined spatial properties, such as blue for lake, green for grass and etc. Based on the datum of architectural terrain, computational geometry and genetic algorithms, the optimized spatial locations of buildings will be evalu-

ated according to the environmental factors such as best scenic spots or region of water. The genetic processes include space data coding, individual adaptive evaluation, selection and alternative steps.

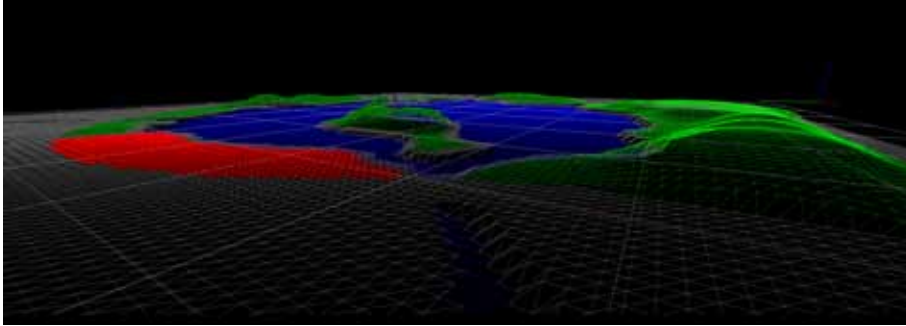


Figure 3. One generated terrain

2. Evolution based on environments' consideration

2.1. TERRAIN CONSIDERATION

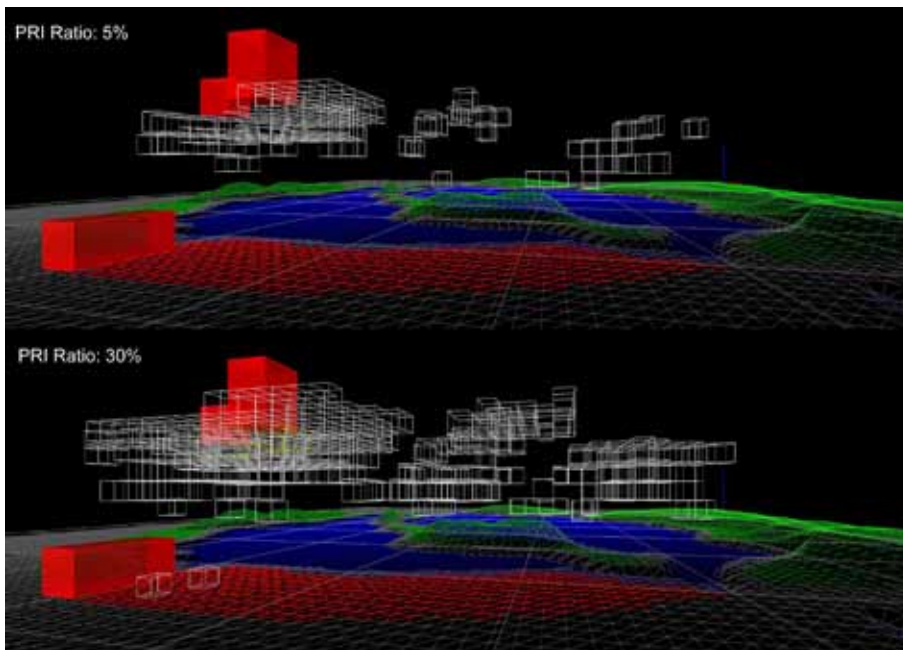


Figure 4. Different ratios of priority for the grey boxes

Benefiting from the generated terrain presented before, different volume of 3D space with different height of z-dimension can be defined above the building site (the above volume of red colour in Figure 3). One result is showed in figure 4, all the small grey boxes can be sorted by parameter named priorities' ratios (PRI) where the positions were iterated and calculated by the amount of "water pixels" the grey boxes can "see". (See figure 4 above: 5% of the best positions occupied by grey boxes, and 30% of that presents in below case).

Taking three red boxes which will be set as the main structure of the building later as an example, they are generated at random positions in figure 4, and then the three red boxes as agents will move or rotate automatically to try to intersect more grid grey boxes to get higher "scores" of better views, meanwhile, all the reds boxes cannot be intersected by each other (see figure 5). The process makes frameworks of which the approximate locations for buildings in 3D spaces and all the buildings have got resources for best views from the local terrain context. Any other restrictions of environmental factors, such as viewpoints of 3D objects, can be set as goals for the process of program evolution. The dynamic evolving process applies all red boxes with biotic characteristic, and it takes several seconds for the three boxes to get balanceable locations where every box can get their best fitness for goals predefined previously.

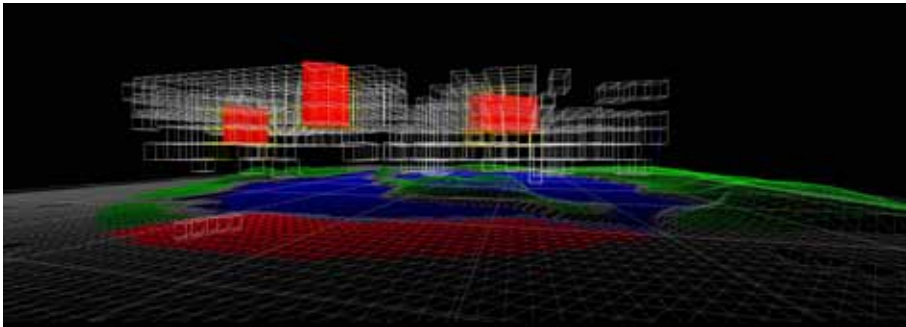


Figure 5. Red boxes search for best locations

Originating from a real estate project, the tool added any other building restrictions of environmental contexts, such as simple calculation of sunlight (Java solar package presented in section of 2.2), systematizing package for architectural functions of topological relationship developed before and also tested in diversiform sites. Moreover, two other small tools were developed for the real project. The first one employing an algorithm of 3D convex was for enveloping the three boxes (see figure 6); and the second one was for the styles of the main structure of red boxes, any patterns such as Voronoi Diagram, Delaunay

Triangulation were tried, but finally an algorithm for plane split was adopted. The detailed introductions for the two programs omit here, the achievement of the real project presents in figure 7.

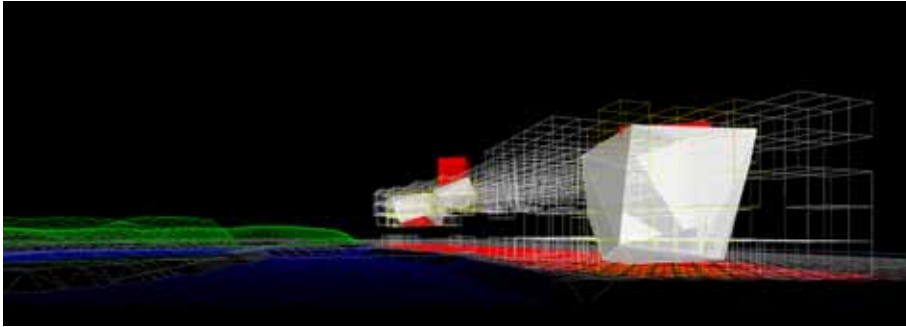


Figure 6. Architectural envelope of convex.



Figure 7. Perspective for the real estate project

2.2. SOLAR CONSIDERATION

Solar system involving in any knowledge of astronomy needs to be considered as a climatic condition of architectural environmental context, and it plays an important role in architectural design. Some software can be found for solar considerations in Architecture, such as *Ecotect* or even *AutoCAD*. However, these kinds of software are normally developed for verifying an accomplished layout of architecture, and they can't tell architectural agents how to evolve for getting a higher genetic *fitness*. During the evolution of *Genetic Algorithm*, computer program needs to get tens of achievements per second for processes of *selection*, *crossover*, *mutation* and etc., which *Ecotect* and *AutoCAD* are

also incompetent. Simpler but more efficient java package was developed into our group.

In the design of apartment buildings, some restrictions need to be considered, such as insolation duration, height of buildings and design values of cantilever of balcony, the developed solar package combines sunshine calculating under various conditions and integrating it into a digital tool of Java program. During process of *Genetic Algorithm*, it is competent for verifying and contrasting *fitness* of next generation with evolution *goal function* predefined. The achievement which shows different colours in various 3D positions is presented in figure 8.

The Java solar package involving complex geometrical algorithms can be employed in different locations of the whole world. All the parameters can be changed and calculated easily during the running of a program, such as duration of sunlight needed for local houses in one day. All the current algorithms are perfect for verifying results of design. However, if applying the technique to *Genetic Algorithm*, which need to set solar parameters for *condition* of individual *seeding selection*, *goal functions* for evolutions and iteration system for more than ten generations per second, the current technology seems incompetent to its ambition.

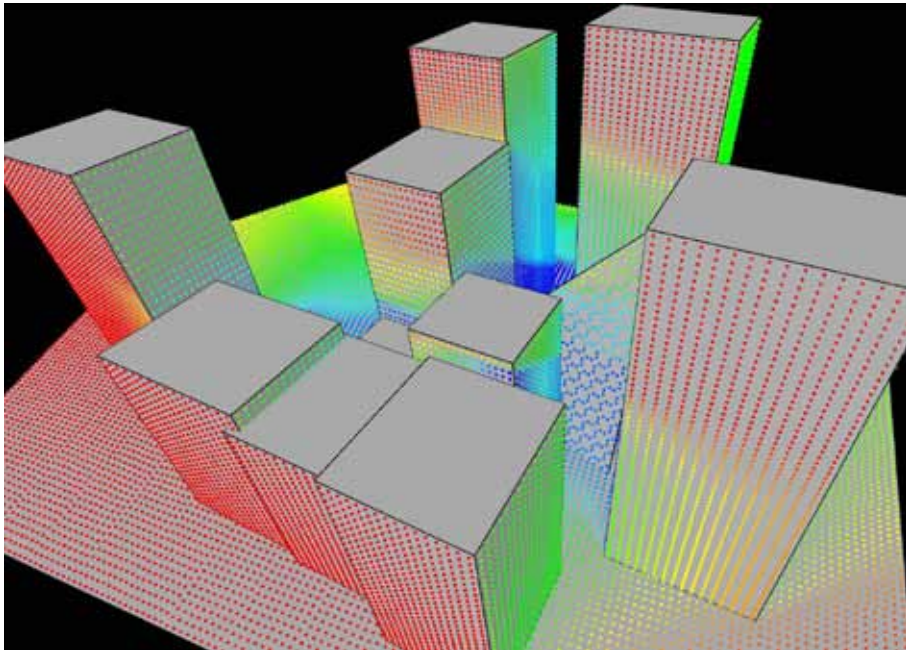


Figure 8. Testing for java solar package

Besides improving the efficiency of current algorithms, our Java package set *Adjacent-Searching-System* for detecting neighbours need to be considered during solar calculation of one building. *Voronoi Diagram* set a good algorithm for both defining and finding adjacent units. Let's take a look at the figure 9 and imagine that a building site locates somewhere in the Northern Hemisphere (sunlight comes from south). Take the agent (or buildings) in the tessellations as considering objects, and focus on finding the agents which "r" will cast shadow on them. All tessellations marked "o" those who locate to the south of "r" needn't to be considered.

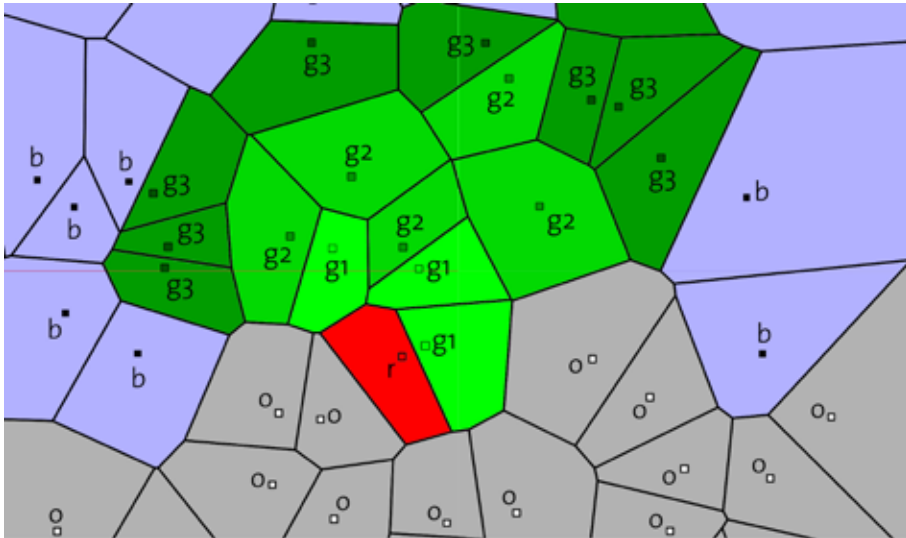


Figure 9. Adjacent-searching methods

Two rules are set for finding tessellations named "g" that "r" which will cast shadow on: one is that we may set the depth of program should search, for example, if the deep set 1, and then 3 of "g1" should be considered; if the deep is 3, and then three of "g1", 5 of "g2" and 9 of "g3" will be taken into account. All the "g" will be detected to confirm whether "r" will cast shadow, and all the "g" covered by shadow from "r" will be stored in a list. The second rule: if "r" cast shadow on one "g3", and then all the adjacent tessellations of "g3" will be taken into account for detecting whether or not they get shadow from "r", and the operation will iterate within tessellations named "b". By such means, a mapping between each tessellation and others who may cast shadow to it will be established. Similarly, a mapping of all tessellations which receive shadow from others can be established.

The algorithms presented above show simple principle employed in

developed Java package, and the whole agents are just represented by points. For the real architectural projects, the points must be transformed or meshed with real 3D geometries (see Figure. 8). Taking residents or apartment planning as an example, many countries set times of duration for each apartment that should get solar light during worst weather in winter days. Employing the java solar package and *Genetic Algorithm*, many achievements of layout will be obtained within less than one minute. Two achievements predefined with different numbers of building floor and floor area ratios generated are presented in figure 10.

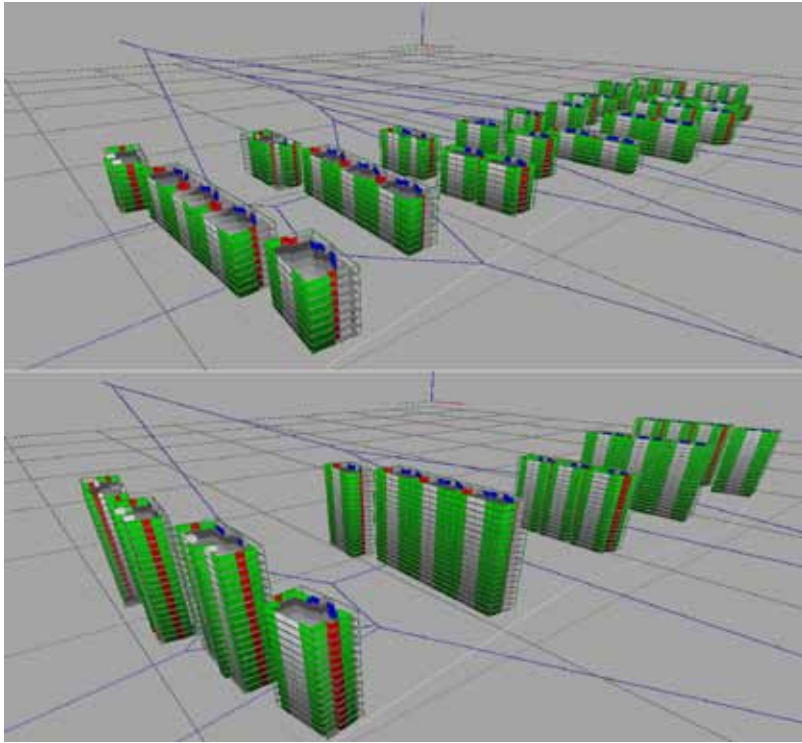


Figure 10. Solar package for apartment design.

2.3 COMBINATION OF PACKAGES FOR ARCHITECTURE

Architectural generative design, which integrates multidisciplinary collaborative thinking in unconventional ways, still lacks both basic theoretical guidance and systematic methodologies. Our Java packages based on contexts of terrain and solar are powerful for early architectural design, any other Java package involving architectural environmental contexts are being developed

to implement the solution for architectural design. These Java packages include not only the geometry algorithms classes for implementing the basic shapes of architectural types, but also the utility classes based on the models for real estate projects. In real application, there is no rigid way for employing these packages, and the generative approaches for architectural design are extendable and flexible, which can be implemented as effective models for dynamic applications that run on real time requirements. All the requirements on performance and availability of detail applications have pushed the research on extracting prototypes in Architecture. The widespread availability of the digital techniques brings about great flexibility and facility to architects, however, it also brings about a series of new problems and challenges to the traditional architectural methodology.

3 Summary

Building environments contain many factors that need to be derived from real projects, and each prototype must be developed from basic architectural principles. Generative design based on architectural rules and controlled by programming logic embodies an operable and flexible methodology for all architects. However, traditional architectural methodology in architecture is increasingly threatened by increasing globalization of digital techniques, such as buildings showing strange shape are attractive to clients and etc. rather than improving quality of architectural spaces and consideration of engineering budget.

Our generative tool provides a design system for the early stages in architectural design. Employed the techniques embodying humanistic characteristics simultaneity, concept of architectural design methodology can be redefined. Digital techniques supply simulative tools to create unparalleled output, which is the 'generator' for new environmental contexts, In accordance to its development prosperity, generative methods applied in the artificial world will endow architecture with the aesthetics jocundity through the approach of Artificial Intelligence and Artificial Life System.

GRAPH VISUALISATION IN COMPUTER-AIDED DESIGN

An exploration of alternative representations for Generative-Components™ Symbolic View

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Abstract. In this paper we explore graph models used to illustrate the relationships between elements of designs in computer-aided design (CAD) systems. We discuss common limitations and ways to make such representations more usable and interactive. In order to study common problems of symbolic representations in CAD systems, we conducted a survey of a number of CAD applications that employ graph representations in their interface and provided comparative analysis of the properties of graph representations in these systems. As a case study we used Bentley GenerativeComponents™ (GC) system - a parametric CAD application that uses graph (“symbolic”) view to visualize the structure of design. We conducted series of interviews with expert GC users that revealed many limitations of the GC symbolic view. To address these limitations, we developed alternative representations of symbolic view that aim at enhancing user experience with the system and reviewed these with expert GC users. As a result of our study, we developed a set of interactive prototypes using SHriMP¹ visualization tool and Processing programming language. These provide improved ways of user interaction with symbolic representation, including better readability of the graph and, as a result, an improved support for design model analysis.

Keywords. Graph visualization; visual interfaces; CAD systems; visual interaction; node-link diagrams.

1. Introduction

Spatial thinking and graph representations are becoming more common in software applications. The use of graph representations varies from one domain to another, and the growing use of visualizations advocates its commonality among individuals in different fields. The complexity of parametric modeling makes the use of visual representations essential. Many graph or node-link representations have been widely used in these applications. In this paper we focus our study on the symbolic view of GenerativeComponents™(GC) software.

GC is an associative parametric design system that gives architects and engineers new ways to explore alternative building forms efficiently. GC captures and graphically presents both design components and abstract relationships between them. The symbolic model window displays all features, geometric and non-geometric, currently existing in the model. This paper looks at the GC symbolic view as an example of graph visualization in CAD applications.

The target audience of this paper are designers and researchers of CAD systems as well as researchers interested in application of visualization methods in real tools. This research could be beneficial for them in several ways. The case study described in the paper could provide more insights into ways people actually use CAD applications and the issues they have to deal with to complete their tasks. Our conclusions provide list of interactive features that could be applied across multiple CAD systems that use symbolic/schematic models in their design. This would help to improve comprehension of design model and promote more effective visual interaction with such systems.

2. Background and related work

Our work is based on findings from recent information visualization and cognitive science research. This includes issues in interpreting visual attributes (Irani and Ware, 2000), specifics of human information processing (Carpenter and Shah, 1998; Huang and Eades, 1995; Huang, 2007), use of colour (edge detection, emotional response to colours) (Ware, 2004), data representation (level of detail, visual comparisons, techniques for representing large datasets compactly) (Zhao et al, 2005; Herman et al, 2000; Herman, 2001) and Gestalt principles (Ware, 2004).

Research states that the size of the graph is one of the key issues in graph visualization: as it grows, its comprehension reduces (e.g. Herman et al, 2000). In this study we use research results from visualization of graphs, networks,

node-and-link diagrams, hierarchical repositories and methods for reducing the complexity of these representations.

One of the approaches to reduce graph complexity described by Ware and Bobrow (2005) suggests that the use of interactive techniques, including static and motion highlighting, can facilitate the process of getting information from graphs. Hao et al (2000) discuss an invisible link technique for linking a large highly connected graph without cluttering the display. This way only the primary links are shown to user, which makes it easier to focus on the hierarchy of interest. Herman (2001) concentrates on the use of metrics, as a measure associated with a node or an edge to be used for large graphs. The metric values can be translated into visual attributes like color and saturation so that the emphasis is put on more important nodes and edges while hiding elements with low metric values.

An important issue raised by Shneiderman and Aris (2006) is interactivity, and the ability to control node placement and link visibility in order to reduce the clutter and control the comprehensibility of data. Namata et al (2007) suggest the use of multiple coordinated views for network visualizations. This way graphs may be viewed and explored in parallel. In our research we propose methods to accommodate this functionality to GC symbolic view by suggesting the keymap (or an overview) of the graph or suggesting the use of two different graph layout representations: one for showing the sequence of creation, the other one for showing the dependencies. Other methods to reduce the complexity of the graph include elastic hierarchies (Zhao et al, 2005) as a way to combine different types of diagrams to reduce the space; algorithms for hierarchisation of complex, highly connected graphs (Mukherjee et al, 1995); and subdividing the graph into sub-graphs of manageable size (Herman, 2001).

The application of research studies mentioned above lays a foundation for our guidelines and interactive prototypes.

3. Software review

As a part of our research, we reviewed several software applications that have graph-based representations in their design including: Quest 3D™, 3D StudioMax™, CATIA™, GrassHopper™, and SolidWorks™. We compared graph interfaces of these tools to the symbolic model interface of GC. This review includes techniques and features that are provided in each system and the tasks that users accomplish using these features. Comparison of the tools is summarized in Figure 1.

During the time when this research was being conducted, the developers of the GC changed the symbolic model to a newer version (see Figure 2 for

comparison). We were glad to see that in the new version some of our concerns were addressed. For example, search and auto layout features have been added to the new version. However, there are remaining issues, discussed below. For comparison we include both old and new versions of GC's graph representation.

	Quest 3D	3D Studio Max	CATIA	SolidWorks	GrassHopper	GC (OLD)	GC (new)
relationship	attributes	highlighting	highlighting	highlighting	attributes + highlighting	highlighting	highlighting
shape	rectangle + square	rectangle	text	text + icon	rounded rectangles	circle	rounded-rectangle
use of icon	x	—	small icons	x	x (switch to text)	—	x
color	gray + green	multiple	no color-text based	x	multiple	multiple	blue with gradient
label's position	on the node	on the node	next to icon	next to icon	on the node	on the node	on the node
link (edge)				No lines, only lists			
zoom	x	x	x	x	x	x	x
search	x	real time	x	x	—	—	partially
edit in place	x	x	x	x	x	—	—
annotation	x	—	—	x	text/sketch	—	—
view	single	multiple	multiple	single	single	single	single
selecting	multiple	multiple	multiple	multiple	multiple	single	single
grouping	x	—	—	x	x	—	—
filtering	x	—	—	—	—	—	—
hidden nodes	x	disappears	gray	gray	gray	gray	gray
layout arrangement	manual	auto/manual	auto/manual	—	auto/manual	manual	auto/manual
snap shot	x	x	—	x (gray)	x	—	—

Figure 1. Comparison of graph models in CAD systems.

From one CAD application to another, the approaches to the same activity are different. Based on our analysis, the graph representation of the Quest 3D™ is the most appealing among the applications that we reviewed. It provides user with multiple possibilities for graph interaction and exploration, such as edit-in-place, annotations, grouping, filtering and search (Figure 1). One feature of Quest 3D™ that is worth mentioning, is the shortcut option that provides the ability to create a custom node anywhere in the graph that behaves like a quick link to the desired part of the graph. Another ability is the illustration of the attributes of each node in the graph. The attributes of each node are shown as black squares attached to the bottom of the node. This way the understanding of the relationship between each two nodes becomes more intuitive.

On the other hand, being able to select a node and move all the dependent nodes at the same time is a useful feature in 3D Studio Max™ that helps the user to make a better sense of the graph.

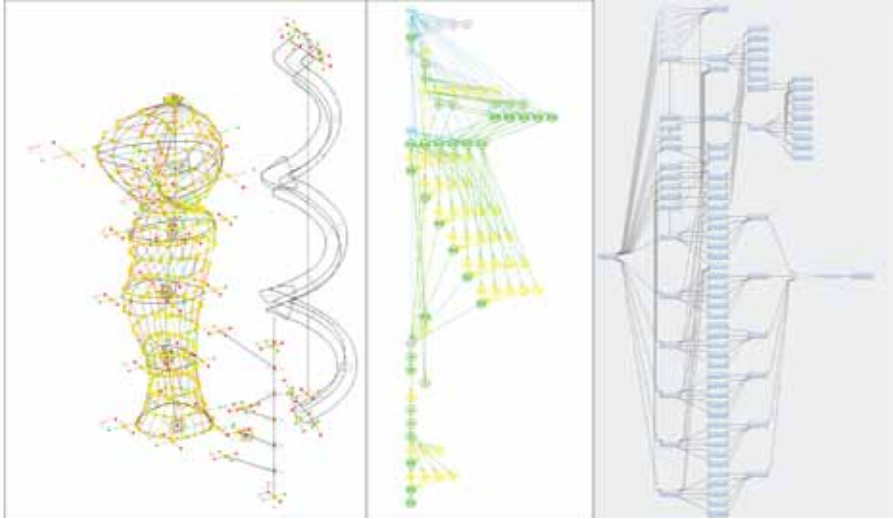


Figure 2. Example of GC Model view (left), old symbolic view (centre) and new symbolic view (right).

CATIA™ has different types of graphs that show the model. The main tree graph is based on the creation sequence of the features. Nevertheless, one can see the structural relationships in a graph as well as parent and children dependencies. Different expansion levels in the graph along with zooming of the selection are the highlights of CATIA™ graph representation. Highlighting the subsequent nodes of an object in the model by hovering the mouse on the parent node is a feature that users can benefit from in the SolidWorks™ graph representation. Ability to add annotations both in text format and by sketching is an interesting feature in GrassHopper™ that makes it more intuitive for users to work with.

4. User feedback

As a part of our research, we conducted semi-structured in-depth interviews with six expert GC users, and online interviews with three expert users. Through conducting these interviews we were trying to understand the goals and purposes that GC symbolic view was used for, and the nature of problems that users had to face during the interaction with the system. The questions addressed issues such as reasons for using symbolic view, desired functionality, ability to make sense of the model, preferred visualization capabilities, common problems, and layout issues.

We found that users worked with symbolic view primarily in order to understand the relationships and connections between nodes, for monitoring the process of model creation, searching for objects, and navigating the graph to get basic understanding of model's structure.

Problems that our participants expressed included: meaningless colors, no grouping functionality, no multiple selection for nodes, no search, no filtering options, no means for isolating parts of graph, no automatic layouts, and visual clutter that appeared with the increase of the amount of elements were the main problems GC users were dealing with. However, as we mentioned earlier, some of these problems have been addressed partially in the new version of the symbolic view. For example, the new symbolic view supports search feature in the graph. Four automatic layouts have also been added to the new symbolic view.

In the following sections we propose solutions to the above problems, and demonstrate them in interactive prototypes of GC symbolic view interface.

5. Investigation results

Based on our study, we identified and listed the features that need to be added to GC symbolic view to improve its comprehension. These features include following:

- Grouping of nodes to reduce their amount
- Multiple selection: selecting several nodes at a time
- A way to differentiate types/importance of nodes: colour, shape or size
- Better default algorithm to arrange the nodes
- Marking of important nodes
- A way to differentiate types/importance of links
- Search functionality
- Filtering: show/hide types of nodes or links
- Annotation or comments in the graph
- Edit in place: basic editing right in the graph
- Isolation of parts of the graph
- Levels of graph detail, key map
- Recording/history functionality (e.g. snapshots of previous design states)
- Layout arrangement algorithms
- Ability to move child nodes with parent nodes
- Highlighting of dependencies for the selected node

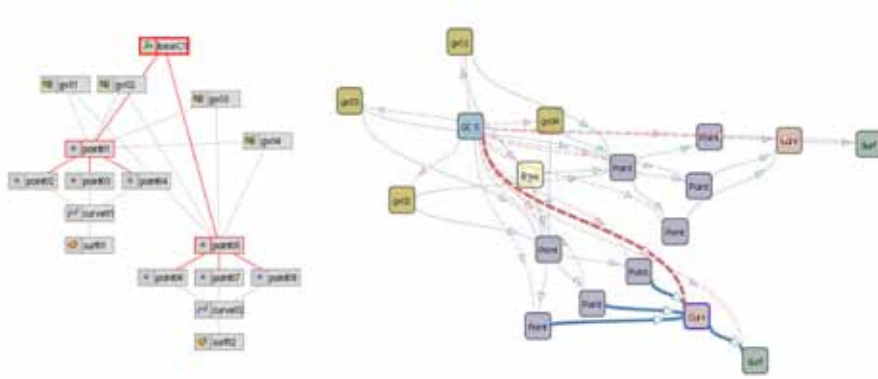


Figure 3. Interactive prototypes using Processing programming language (left) and SHriMP tool (right).

6. Prototypes

We created several paper prototypes and interactive software prototypes to demonstrate the ideas of possibilities for graph visualizations in GC. For our interactive prototypes, we tried two approaches. First, we tested our early ideas by creating a graph in Processing™ (Figure 3, left). The prototype built in Processing uses icons for differentiating between types of nodes as well as interactive highlighting and node rearrangement techniques. In the second iteration, we demonstrate our findings using the SHriMP visualization tool.

The SHriMP interface includes search, filtering and highlighting options, customizing node and link colours and shapes, label styles, zoom modes, automatic layouts (e.g. radial, circular, spring, treemap), thumbnails, snapshots and manual layout rearrangement functionality. This means that all the graphs built with SHriMP are interactive, editable and allow exploration of the graph model to facilitate its comprehension. Figures 3 (right) and 4 show screen shots of SHriMP to express the desired features in the graph visualization. For example, Figure 3 (right) demonstrates the possibility of differentiating between types of edges and use of colour to differentiate between the types of nodes. Figure 4 (right) uses size of nodes to show importance levels and colour to show node types. It also uses curved edges, which increases user ability and speed of tracking paths. For better graph comprehension and reduction of clutter, the edge filtering option is included in this example.

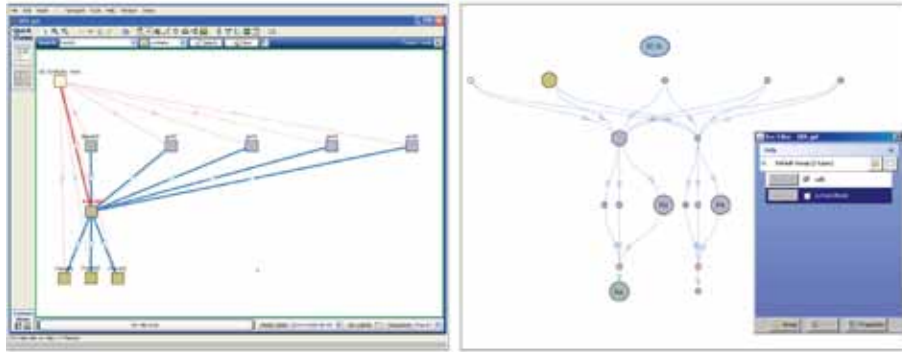


Figure 4. SHriMP interactive prototypes.

There are essential features that every graph representation should support in order for users to be able to interact with the graph. These features are: multiple selection, search and edit-in-place. Multiple selection eases graph arrangement. Further important features are: meaningful colour coding (type and relationship differentiation), which improves comprehension, and multiple views of the same graph, so one can study the graph in more detail and with different representations.

We discovered that both manual and automatic layouts have their advantages and disadvantages. For example, having system do the arrangement in a predefined layout is fast and reliable, however the ability to re-arrange the nodes in a way that makes more sense for the user is equally important. In this case, snapshots of the node arrangements may be useful, so users can record as many node arrangements as desired.

Grouping the nodes is a way to reduce the number of nodes in the graph. However, this encapsulation comes with the cost of losing or hiding some of the links and relationships. By grouping several nodes, one node that represents all the grouped nodes with links that show connections of each member inside the group with the rest of the graph, is created. This way, it becomes impossible to see which node in the group is connected to a certain node outside it unless that group is opened. In addition, the relationships among the group members become invisible.

From this study we conclude that the context of a specific visualization is the primary criterion by which the decision of whether to apply a specific method or not, should be made.

7. Discussion

Design considerations and interactive prototypes for symbolic view are initial steps in improvement of this important part of GC system. Additionally, the design principles, visualization techniques, and interaction features discussed in this paper can easily be generalized for designing and/or improving graph representations in other CAD applications. This work is an exploratory study, and we suggest the above analysis and suggestions to be further developed and validated with system expert users.

In software review we mainly focused on the CAD applications, which might not cover the complete area for the hierarchical graph representations. On the other hand, we tried to compare the appropriate applications that have similar usage as GC. By doing so, we realized that GC symbolic view lacks very basic visualization functionality and does not provide interactivity.

In this study we focused on the general visualization principles and perception issues rather than on specific user tasks. However symbolic representation may highly depend on the context of work the user is performing (Purchase et al, 2001). Undoubtedly, task-based user evaluation for the proposed solutions should be considered as the next phase of this project. Through this type of evaluation interactive prototypes should be tested on their ability to support users at various stages of the design process.

8. Conclusion

In this paper we presented a study that explored graph views used in CAD software and provided a set of features that can improve user interactions with this type of representations. Our results take into account the specifics of human visual information processing and perception, findings from visualization science and graph visualization research. We used the example of GC (a parametric CAD system) as a case study. Features that we consider important to be present in symbolic graph representations include search function, isolation of the part of the graph, interactive highlighting, filtering, grouping, keymap, multiple selection, types of zoom and layout algorithms. The primary goal of this research is to provide ways for improvement of current graph functionality in CAD systems by supporting interactivity, reducing clutter and promoting better and easier understanding of the model by taking advantage of various visualization approaches for nodes, links and layouts.

Endnotes

1. www.thechiselgroup.org

Acknowledgements

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DESIGNING ELASTIC TRANSFORMABLE STRUCTURES

Towards Soft Responsive Architecture

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Abstract. This paper discusses the issues of designing and building environment involving spatial conditions that can be physically reconfigured to meet changing needs. To achieve this architectural vision, most current research focuses on the kinetic, mechanical systems and physical control mechanisms for actuation and structural transformation. Instead of the ‘hard’ mechanical joints and components, there is an unexplored ‘soft’ approach using lightweight elastic composite materials for designing responsive architectural skins and structures. This paper investigates the new possibilities for the manipulation of various architectural enclosures using ‘soft’ and elastic transformable structures, in response to environmental, communication and adapting to various contexts. This approach intends to minimise the mechanistic actuations and reduce weight for such operations. Therefore, this research introduces two modules (a tetrahedron and a cube) as responsive spatial models to test the potentials and limitations for the implementation of elastic materials with responsive capability towards reconfigurable architectural enclosure. Despite their individual differences, these experiments identify a trajectory for new possibilities for elastic architectural components that are more appropriate for ‘soft’ responsive architecture. We argue that this approach can provide an early hypothesis for design responsive architecture with a mix of passive and active design strategies.

Keywords. Elastic; transformable; soft; responsive.

1. Transformable structures for responsive architecture

“Responsive architecture” was coined by Nicholas Negroponte in the mid

seventies (Soft Architecture Machines) when spatial design problems were explored in responsive space (Sterk, 2003). There are precedents for responsive architectural spaces that can be transformed and reconfigured to accommodate different usage. The first precedent: Villa Girasole, the rotating house built by the engineer Angelo Invernizzi in 1929-35 Marcellise, a completely revolutionary idea of a rotating building designed to constantly capture sunlight and the use of eco-compatible energy source. In addition, Gerrit Rietveld used sliding partitions to allow spaces to be responded to different uses in his Schroeder House, 1924 (Butler and Oudsten, 1989). Recently, Shigeru Ban's 9 Square Grids House has a similar approach, a contemporary interpretation of the conventional Japanese house with sliding partitions as large cabinets to store blankets and mattresses during the day and provide privacy at night (Ban, 1998). However there are several shortcomings to these approaches that have restricted their implementation. In general, there are only limited possible configurations, and while the partitions are produced as lightweight as possible to allow inhabitants to move them manually, making them poor thermal and sound insulators, the process of reconfiguring a space is fairly labor intensive (Weller and Do, 2007).

In parallel, computationally generated transformable structures have also been a focus of current digital era. When we consider responsive architecture composed by transformable structure, we are forced to confront issues of human power, space control, environmental manipulation, material economy, operational effectiveness, and energy investment (Sanchez-del-Valle, 2005, p.137). Furthermore, contemporary responsive architecture in general is built on the convergence of embedded computation (intelligence) and a physical counterpart (kinetics) that satisfies adaptation within the contextual framework of human and environmental responsiveness (Fox, 2009, p.381). The integration of these two areas will provide the environment that is capable of reconfiguring itself and automating physical change to respond, react and be adaptive. This metaphor will lead to a purpose that structure can be reduced for space-making through the ability of a singular system to facilitate multi-uses via transformative adaptability.

2. Soft Responsive Space

Recently, the work of dECOi: Aegis Hyposurface has attempted to integrate two facets of architecture: responsiveness and transformable structure, to create and investigate responsive architectural facades and installations using high-tech mechanical solutions. However, this solution involving '*hard*' mechanical components like multiple pistons to actuate transformation always comes with high energy consumption and complex mechanism. Is there an alterna-

tive to this approach? There is a need to further explore a new possibility to address the '*soft*' elastic architectural components like elastic strings, textile and silicone latexes towards responsive architecture.

Since the '*soft*' approach of architecture introduced during 60s and 70s, there is not much progress in this experiment and research area of architecture (Negroponte, 1975). However, in order to achieve this architectural vision, further exploration of kinetic mechanism and materiality is needed. Instead of investigation towards the conventional mechanistic approach, this research explores for the use of day-to-day '*soft*' elastic materials for constructing kinetic and responsive architectural model. The purpose of this investigation takes the position that a more organic versus mechanistic approach to transformable structures, one that capitalises on material properties rather than technologies of connections, provides an opportunity to holistically address both performance and aesthetics in soft responsive architecture (Khan, 2009). Although works by ONL and HRG, such as project Muscle (Oosterhuis, 2003) aimed to demonstrate a soft responsive space, the pneumatic mechanisms are highly power consuming and less consider the potential of elastic memory of the soft structure for passive actuation and surface porosity. On the other hand, the work of Omar Khan: Gravity Screens provide an alternative approach that the surface constructions form results from gravity's effect on their elastic material patterning. These elastic mutable screens provide possibilities for responsive space that can mutate from circulation corridors to room clusters (Khan, 2009). However, Khan's work just provides a starting platform for soft responsive architectural idea and it is still unexplored territory to expand this potential of responsive architecture, from '*hard*', to '*soft*' approach.

There is a need for low-tech passive design strategies which can generate responsive architectural prototypes without complex mechanical actuations. Thus, this research aim to explore the application of elastic transformable structures, such as exhibited in elastic material systems, for fabricating low-tech and soft responsive spatial modules. The elastic nature of these structures is able to accommodate responsive mechanisms with passive elastic memory while minimising the energy and weight required for actuation. Although the premise of energy and maintenance of this application are concerns in this research, they are not included in the scope of this paper. We argue, as an early hypothesis of this research, that elastic transformable structure can provide designers with a mix of passive and active design strategies for manipulate soft responsive space through the testing of scaled spatial modules. Therefore, this paper will expands the repertoire of responsive architectural design solutions using accessible '*soft*' component such as elastic materials integrated contemporary digital sensing devices and parametric design tool.

3. Design Process

The purpose of the design process presented in this section is to design elastic transformable structures using the soft approach of manipulating responsive space. The whole process undergoes iterations of physical and digital modeling and fabrication (Figure 1). Through each step of the process, digital data is exchanged between digital and physical models. This process is called form fostering, which bridges the physical and digital through exchanges of digital data (Salim et al, 2011). Parametric models can be associated with real time data from sensors, which stream data from physical environment, as input to drive the parametric variations in the model (Salim et al, 2011). The parametric model becomes the platform for simulating the behaviours of the elastic transformable structures in the design stage. In general, the design process of elastic transformable structures consists of four factors as listed in subsections 3.1-3.4.

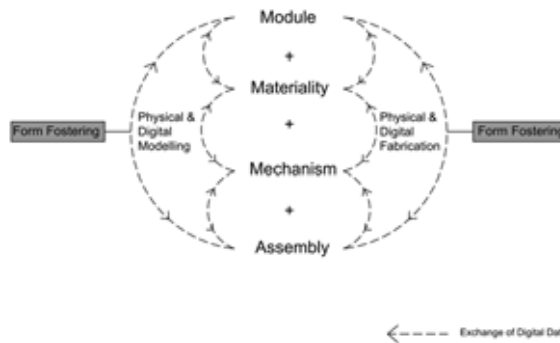


Figure 1. Diagram of design process in four areas towards form fostering.

3.1. MODULES

The first stage of the design requires modular components to be sketched, modeled, and fabricated. They are represented in the form of parametric models as part of experiment process.

3.2. MATERIALITY

It investigates day-to-day, accessible and affordable elastic materials such as rubber band, elastic spring and balloon for physical implementation.

3.3. MECHANISM

Mechanism is looks at the new possibilities of these elastic materials to produce

simple mechanisms like joints, actuators and hinges that could become an alternative toolkit compared to conventional mechanical approach.

3.4. ASSEMBLY

The last process is the assembly of the modules in order to achieve transformable structure that displaying elastic properties to respond digital and physical adaptation. The following section discusses form fostering experiments which include two different modules – an Elastic Tetrahedron and adaptive Cube, which are presented to demonstrate some experiments which include the proof of the early concept for elastic transformable structures that are simulated by computational methods for their active and passive modes responding to changes in the environment.

4. Experiments

4.1. THE ELASTIC MODULE

In general, initial idea of the elastic module has the ability to reconfigure itself - to automate physical change to respond, react and adapt. However, this idea needs further exploration especially in terms of energy and weight. When we argue a structure that moves in whole, or in parts, is like a machine. A machine applies energy to do work and energy use is unavoidable. Thus, this section demonstrates two experiments that address this issue by using lightweight orientated and accessible transformable structure with elastic ability to reduce energy and weight that respond to stimuli by changing their form. It aims to test this hypothesis on two modules. The intention of these modules is to propose general directions to be applied to solve the ‘soft’ technical responsive design and energy issues for future works. The Elastic module discussed these issues focus on the new possibilities of elasticity towards soft responsive architecture in the following areas:

- **Elasticity as structure.** The structure of architectural components such as roofs, ceilings and walls can be contracted and expanded to increase flexibility in the use of existing internal or external architectural space.
- **Elasticity as membrane.** A ‘*soft*’ architectural surface will be explored through harnessing elastomer (elastic polymer) properties for the feasibility of implementation such as passive amorphous building membrane harvesting kinetic energy through wind or sunlight.
- **Elasticity as actuation.** This research and design looks at the new approach of elastic material as actuator for it lightweight and minimising the use of mechanistic joints and piston. For instance, pneumatic air harnessing balloon

or muscle for global actuation and reduce weight and friction between part.

4.2. ELASTIC TETRAHEDRON MODULE

4.2.1. Materiality

The module of Elastic Tetrahedron is using accessible elastic string as a primary material and hollow straws fabricate the Elastic Tetrahedron module used as supportive structure.

4.2.2. Mechanism

It is to form an elastic skin for existing building to response proximity through pneumatic air balloons actuation in order to contract and expand parameter to manipulate the interior spatial condition. It is capable of changing various states while force applied and return to the original state if force released (Figure 2). This behaviour provides the opportunities to minimise the energy for local actuation and attempt to develop a low-technological approach to performance structures that possess adaptive and evolutionary personality related to environmental stimuli.



Figure 2. Elastic Tetrahedron is formed by elastic string and plastic hollow straws for their lightweight and flexible purpose.

4.2.3. Assembly

Furthermore, the combination of individual module will form the *Elastic Space-Frames* that assembling more complex formation of elastic structures and behaviour in bigger scale. This experiment is mimicking a simple living organism that responds to human interaction to form a responsive *Shelter*. Therefore, in order to achieve this responsive phenomenon, form fostering technique composed of sensors and actuators is necessary that roughly simulates the biologic behaviour. Firstly, Grasshopper and Firefly parametric software together with Arduino microcontroller and proximity sensors are used

as design tools engaged with this simulation process (Figure 3). Second, the actuation is involved through the use pneumatic air balloon serves as actuator to reduce mechanistic components as mentioned in the section *Elasticity as actuation*. The goal of this parametric model is to be an elastic skin actively responds to the environment with a series of features like flexibility, unpredictability and non-linear transformation that constitute important facets of what soft responsive architecture should manifest (Figure 4).

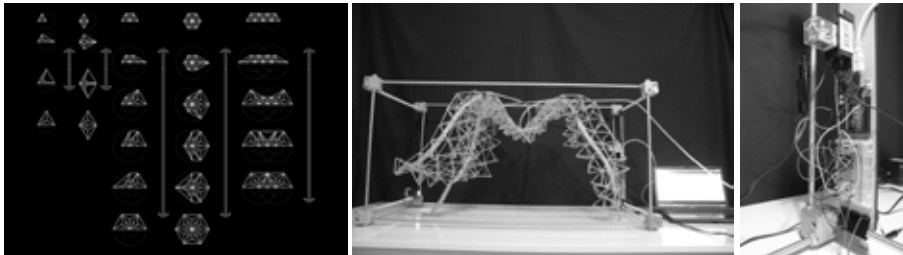


Figure 3. The formation of Elastic Space-Frames (left); The complete module of Shelter (middle); A setup included Arduino microcontroller, relays and breadboard (right).

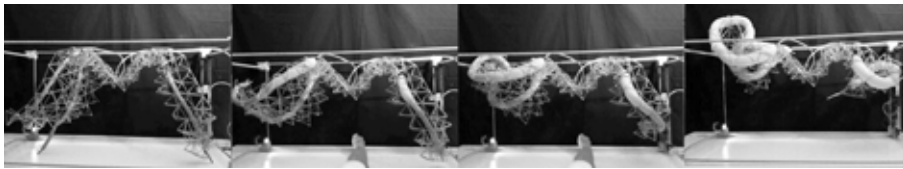


Figure 4. The Shelter contracts and expands responds to the proximity of human intervention and population through the pneumatic balloon as elastic actuator.

4.3. ADAPTIVE CUBE MODULE

4.3.1. Materiality

The elastic and adaptation capability of the structure configuration is the initial goal for this *Cube* module development process. This *Cube* structure model basically is assembled by two components, a hard hollow aluminium tube and soft elastic string for their lightweight and accessibility, to minimise the energy required for actuation, and be able to be continuously flexed along each joint to connect them together.

4.3.2. Mechanism

Furthermore, the actuation system will be a similar approach to the Elastic

Tetrahedron module previously and the pneumatic air balloon is ‘embedded’ in-between two hard and soft materials for actuation in order to adapt various environment conditions. For example, each corner of the *Cube* structure is embedded a sensor to detect the proximity of object or surface and it extends the length of the structure until it reaches the stable state (Figure 5).

4.3.3. Assembly

The purpose of this experiment is to test the new possibility for assembling automated adaptability in architectural structure for unpredictable calamity events such as earthquakes and floods to minimise damage and provide protection.

In addition, the design of this module opens up opportunities to develop of architectural configuration that responds and adapts for uncertainty (Figure 6).

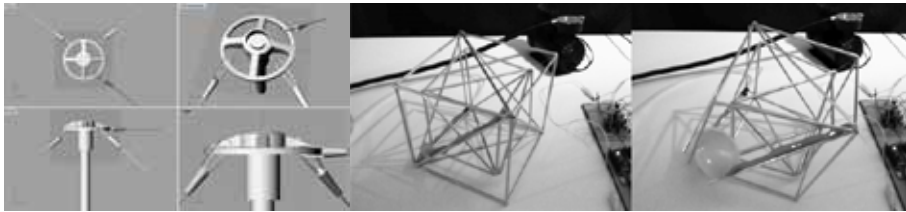


Figure 5. Digital detail of elastic joint that minimise fiction (left); Physical *Cube* structure with sensors and embedded pneumatic air balloon to detect proximity of surface until reaches its stable state (right).

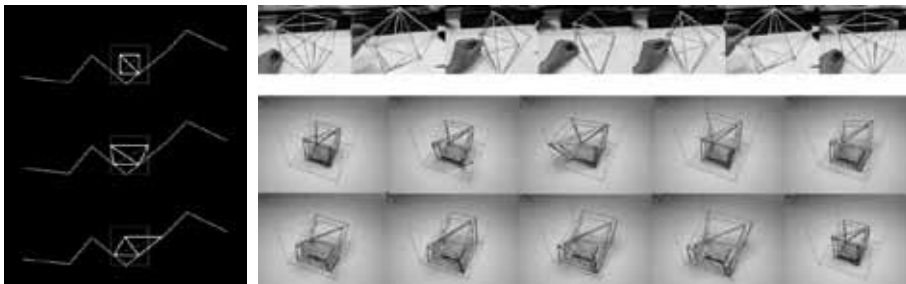


Figure 6. Adaptive *Cube* structure for unpredictable environment (left); Early stage of physical study of the elasticity (above); Adaptability of the elastic *Cube* structure (below).

5. Conclusion and future work

The research presented in this paper introduces the new design possibilities of elastic transformable structures that adapt and respond to environment in

order to manipulate dynamic reconfigurable space. By using the two elastic modules as experiments to test, the aim of these experiments allow new ideas emerge from performing physical and digital modeling. One of the fundamental investigations for this research is testing the '*soft*' approach of elastic structures provide alternative to conventional kinetic approach using mechanical components to achieve responsive architecture. We argue that the '*soft*' and elastic components such as elastic strings, latexes and fabrics demonstrate more appropriate approach for responsive architecture in terms of actuation and deformation as demonstrated in precedent works by ONL and also experiments described in this paper. This approach has been tested by the two responsive parametric models discussed in section 4 and presented the great potential for full-scale implementation in future research. In addition, when applying the computation design tools for the parametric model; the multiple analogue inputs information flows to the responsive algorithm to activate the '*soft*' elastic actuator for the flexibility, versatility and adaptation in transformable structures. The further development of this research attempts to refine this method and explore the simpler and robust prototypes using elastic, lightweight, form-changing materials as structure in order to achieve the dynamic reconfigurable space for functional environmental aspects.

On the other hand, since the property of elastic material makes it problematic as a self-supporting structure, the introduction of embedded pneumatic air muscle as stretchable actuator shown in two modules cause it to stiffen and hence solve certain level of the structural integrity. This design approach is leading to the lightweight structure that allows '*soft*' elastic architectural skin to transform from thresholds to enclosures. This approach implemented in the process of designing holds significant potential for further exploration towards the form-changing materials as platform of convergence in-between transformable structure and responsive space. The form-changing materials such as Ethylene Tetrafluoroethylen (ETFE) embedded with photovoltaic cell, Shape Memory Alloy (SMA) and Electro-Active Polymer (EPA) that respond to environmental and communication stimuli will provide the potential for full scale architectural applicability of elastic transformable structures; and harvesting energy for self-sustainability while reducing mechanistic components. They also enable real time manipulation of elastic capabilities for transformation demonstrated by the two modules that utilise the novel design framework proposed in section 3. This future research is offered a practical methodology for conceiving a responsive architectural envelope system that synthesizes passive design concerns with the feasibility factors of fabrication and construction goals. Thus, in relation to the hypothetical experiment, the purpose is to find a range of possible integration of responsive skins and structures that

can be applied to various architectural components such as facades, walls and roofs in general to complete the actual design solution for the future work. These transformable components will eventually serve as second skins for existing buildings intended to potentially improve the interior and exterior spatial conditions.

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GENERATIVE AND PARAMETRIC DESIGN IV

15.	Designing responsive architecture: Mediating analogue and digital modelling in studio	155
	<i>Daniel Davis, Flora Dilys Salim and Jane Burry</i>	
16.	Parametric materiality: Material properties as catalyst for design	165
	<i>Russell Loveridge</i>	
17.	Tree facades: Generative modelling with an axial branch rewriting system	175
	<i>Stuart Hanafin, Sambit Datta and Bernard Rolfe</i>	

DESIGNING RESPONSIVE ARCHITECTURE

Mediating analogue and digital modelling in studio

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Abstract. Prototyping digitally responsive architecture requires that architects know how to program and design electronics. Normally they don't. The challenge for teachers is to teach these skills whilst maintaining a focus on the design potentials of responsive architecture. One method is to teach students to use Input-Output-Process (IPO) diagrams and parametric modelling as pathways into the logic of responsive architecture. The paper discusses the work of students taught this way during a semester long elective. Our analysis shows that IPO diagrams lead to reactive architecture, which matches the current technical limitations of responsive architecture. We argue that mediating analogue and digital models is an essential aspect to successful responsive architecture.

Keywords. Responsive architecture; physical interaction; education; parametric design.

1. Introduction

Parametric models, enabled by a rise in computation, can automatically adjust geometric models in response to real-time data. Unlike solid based digital design methodologies, which use static data to analyse an immobile geometric model, these new parametric tools synthesise dynamic, real-time data to produce a flexible geometric model (Leach, 2009). However, in order to physically construct these flexible and dynamic parametric models, the geometry must be 'frozen' causing a disjuncture where the real-time data no longer influences the geometry. Critics tellingly describe the buildings of Frank Gehry, a pioneer of this method, as frozen music (Garcetti, 2004).

In the construction industry, the advent of computation has lead to buildings that use mechatronics to respond in real-time to data. Often this is for environmental purposes - for instance, opening and closing louvers based on internal air temperature and weather reports - but increasingly mechatronics is being used for spatial effects. In designing these responsive systems, parametric modelling provides one way to visualise the response of a building to real-time data.

Both of these skills - parametric modelling and building mechatronics - could be considered niche specialisations, although this is changing with the rise of consumer level design tools to support responsive architecture. In particular the invention of graph-based parametric modelling software, Grasshopper and Generative Components, and the open source mechatronics platform, Arduino, has lowered the required technical skills necessary to create responsive architecture.

The challenge for educators is to introduce students to these fundamental technical skills, while maintaining a focus on the design potential of responsive technology. The aim of this paper is to better understand how educators can teach architecture students to design responsive architecture. The paper provides a qualitative account of a semester long design elective setup to teach students to design responsive architecture using parametric modelling and mechatronic prototypes. We begin with a summary of past work on the practice and teaching of responsive architectural design, which is followed by a description of the teaching process used in this study as well as the results that come from it. We conclude with a discussion of major challenges and opportunities to the implementation of responsive architecture in practice.

2. Prior work

Responsive architecture is defined by Meyboom et al (2010) as an architectural “system that causes change to its environment.” They use the terms responsive and interactive interchangeably, but for this paper the distinction is made between a responsive system, which reacts to an environmental stimulus, and an interactive system, which reacts to an environmental stimulus with prior knowledge of previous interactions. All of the student projects produced as part the RoboStudio reported by Meyboom et al fall into this former category, and, considering the current state of machine intelligence, it would be highly surprising for any student to produce a conversationally interactive system. In this sense the student outcomes in the Meyboom et al paper and the expectations for the students taught in the elective as part of *this* research, are fairly similar. The key difference is that this paper investigates teaching architecture students to design responsive architecture with parametric modelling

and Input-Process-Output diagrams, where as Meyboom et al focused on the physical prototypes from their interdisciplinary class of architecture students and engineering students.

The introduction of parametric modelling to the design process offers interesting possibilities in simulating the aggregate behaviour of responsive elements, but also poses challenges in negotiating the differences between the reality of the digital world and the reality of the physical world (Salim et al, 2010). Our prior work on responsive architecture in the context of a workshop at Smart Geometry 2009 (Salim et al, 2010) and in the context of an elective that ran over summer at the Royal Melbourne Institute of Technology (Salim et al, 2011), has identified this as critical area of practice requiring further research. The elective presented in this paper builds upon previous studios by introducing parametric modelling and the Input-Process-Output (IPO) diagram as a teaching method.

To a lesser extent, the work in this paper also draws upon prior work by, Moore and Hill (2010) as well as Hu and Fox (2003) both of which focus on teaching students to design and build responsive prototypes, however neither includes parametric modelling as part of course syllabus. The teaching of parametric design is similar to the approach used by Burry (2007), although in Burry's research the students did not physically prototype the designs.

There is a methodological similarity within the prior research discussed in this section. Most of the studies present work from a group of students taught during an experimental studio, and then qualitatively identifying trends in both the students work, and its design history, to reason about the learning outcomes and the challenges facing responsive architecture. This paper takes on a similar methodology by presenting a series of observed patterns in student work arising from a teaching method that uniquely integrates teaching mechatronics with parametric design.

3. Outcomes of teaching responsive architecture

Responsive architecture was taught as a 12 week elective at the School of Architecture in the Royal Melbourne Institute of Technology. The learning objective of the course was to teach students skills in designing responsive architecture, parametric modelling and mechatronics while broadening their general design skills.

The students who elected to take this course had very little, or no experience, in developing electronic systems or building parametric models, although they all had over a years experience using some form of CAD. The students' technical inexperience was a key consideration in structuring the course. It was undesirable, on such a short course, to spend a large amount of

time teaching technical skills prior to the students starting to design, however designing responsive architecture requires some level of knowledge about how to construct responsive models. So the challenge was to enable the students to design responsive architecture while they were learning what it is, and while they were acquiring the skills to prototype their designs. During the first half of the elective, this problem was approached in two ways:

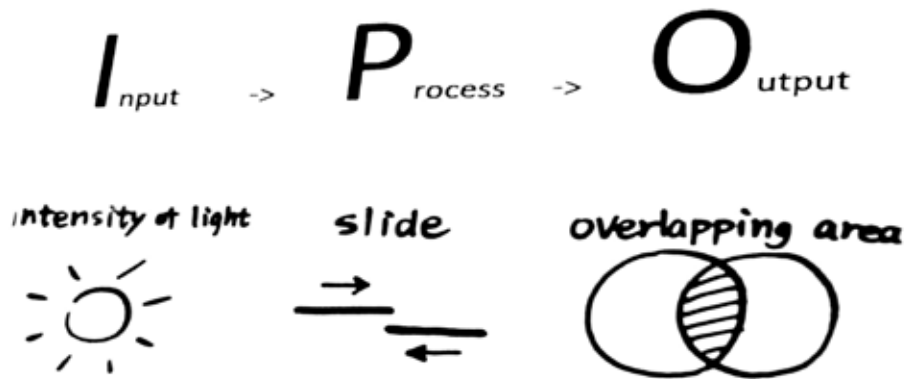


Figure 1. An early IPO diagram of Shuying Zhou's project

1. The IPO diagram: The students were given a conceptual pathway into the design of algorithms using Input-Process-Output (IPO) diagrams. The IPO diagram was developed by IBM in the 1970's as a communication device to describe the main steps of an algorithm (the formation of inputs, a process to manipulate these inputs and the outputs of that process). For the students, the IPO diagram gave them a formal structure to sketch possible responsive behaviours. It encouraged them to describe these responsive behaviours in algorithmic steps, before they knew how to program an algorithm. During the first week of the elective, the IPO diagram was introduced to the students as a mapping exercise where they were invited to use maps, diagrams and images to record data sources within the urban environment of Melbourne, Australia. These data sources were to become the inputs for the behaviour of their responsive architecture. During the second week of the elective, the students were shown how to design system behaviour with an IPO diagram. The students selected a data source they had previously mapped, and found a way to describe a process that would manipulate the input to create the desired outputs. By generating different versions of these IPO diagrams, the students could begin to reason about what response was desirable. The design task set was to create a shelter or pavilion in Melbourne, which reacted to one or more

of the data sources they had previously mapped. At this stage the students were still learning the basics of parametric modelling and mechatronics, so the IPO diagram became a way for them to sketch (in an algorithmically rational way) the behaviour of a system and to communicate their design's behaviour during design critiques to fellow students and tutors. An example of a student's IPO diagram is shown in Figure 1.

2. Workshops: For the first 6 weeks of the elective, the students attended weekly workshops on parametric modelling and mechatronics. The workshops were intended to give the students an idea of the potential of these tools and to give the students the essential skills to generate models with these tools. The students were taught to think about these tools using IPO diagrams. So when using a graph-based parametric modelling tool, they were encouraged to identify the data required for the model (the inputs), to identify what they wanted the model to produce (the outputs) and to construct a process that ties the inputs and the outputs together. This teaching method is different to the teaching method normally employed where the student is taught what each element does within the model, rather than the structure of the model (see any of the Grasshopper training guides for an example of this). The benefit of using the IPO diagram is that the students start to construct their parametric model in a modular way and do not need to be introduced to this concept later on.

In the second half of the elective, the students worked towards designing a responsive pavilion and creating a full scale model of the mechanism from their pavilion. This occurred through a series of weekly design studios where the students would bring both physical and digital models to be discussed and workshopped with the tutors and fellow students. The submission requirements asked the students hand-in both a physical model and a digital model of their design, with the intention the students develop their designs between the two media, but as will be discussed later in this paper, the students tended to lead with one medium and follow with the other. In the final week of the elective the students installed their working prototypes and digital models, which they presented to a panel of external reviewers. A selection of these projects, and the major moments in their creation, are reviewed in the following subsections.

3.1. FISHANTASY

Teng Ge designed this prototype for a responsive ceiling that responds to the movement of the cars on the road it is suspended above. Ge's inspiration was the design of Aegis Hyposurface by dECOi, and the movement of fish when they flock together. Like a flock of fish, the individual components that make up the surface move away from moving objects.

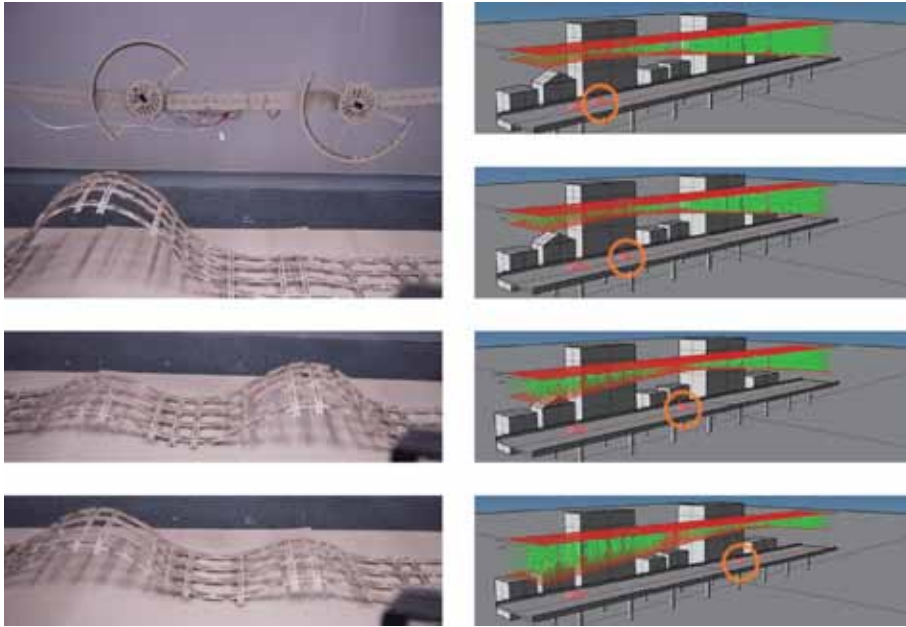


Figure 2. The physical and digital model of Fishantasy

Ge started with a digital sketch, developed in Grasshopper, of an array of components that reacted to an attractor point. In subsequent design revisions Ge refined this to an undulating ceiling that reacts to movement underneath. A major breakthrough on the project was developing a way to create the undulations without every component being individually actuated. Ge achieved this through a series of physical prototypes that explored the connection detail between components to give the right amount of curve in the structure - a subtlety of the material that was impossible to capture in a digital model. In the final prototype, a camera is used to track objects. The coordinates of the objects are sent to Grasshopper where the parametric model reacts to the new set of inputs. The coordinates are also sent to an Arduino board that actuates the physical prototype.

3.2. RESPONSIVE STAINED GLASS SHELTER

This project designed by Shuying Zhou is a bus shelter's roof made from interlocking, multi-coloured, translucent, modular panels. The panels act as gears, rotating in unison to control the amount of shade offered and the pattern of blended colours. Their movement is related to the ambient light intensity, creating more shade (and colours) when it is sunny.



Figure 3. The physical and digital model of Responsive Stained Glass Shelter

Zhou started with physical models exploring a number of possible rotational mechanisms for modular elements around vertical and horizontal axes. She then used Rhino and Grasshopper to simulate and visualise their intended behaviour. The chosen panels were laser cut at full scale and assembled to form one ceiling panel of the shelter prototype. It was only when physically cut that the deformation, friction and tolerances of the modules became apparent, requiring Zhou to refining her design to overcome these construction problems.

3.3. RESPONSIVE WALKWAY AND SHELTER

Intje Siswandi designed a shelter that folded out of the walkway in response to pedestrians walking around it, allowing space for gathering crowds and providing shelter for small groups of people. Siswandi's starting point was a series of Rhino models exploring folded metal plates. The folded plates were readily drawn in Rhino, but it was difficult to predict how these plates would move when actuated. For this reason, Siswandi switched to fabricating a number of physical components to further explore her idea. She continued to develop the parametric model as a replicated rather than an anticipation of the physical models.



Figure 4. The physical model and digital impression of Responsive Walkway And Shelter

3.4. RESPONSIVE AND INTERACTIVE PIXEL FACADE

Sean Seah designed a pixel facade, where each unit has an aperture that can be opened and closed to display information and control the ambient light level.



Figure 5. The physical model of an interactive/responsive pixel facade

Seah's work is inspired by existing urban media facades, which he believes are unresponsive and do not take into account potential contextual human interactions. Fortuitously, he came across an origami inspired method of folding shapes, and developed the geometry to become the iris of his pixels. Like with Siswandi, Seah found it difficult to replicate the folding of the origami unit in a parametric model, although since a pixel was difficult to manufacture, Seah had to use a parametric model to simulate and design the aggregate behaviour of his pixels. In his final presentation Seah created an array of 10 pixels which each individually responded to light, and collectively responded to sound.

4. Challenges facing the teaching of responsive architecture

In reviewing the student work produced from this elective, a few trends emerge regarding the teaching method employed.

Firstly, it is clear that the students, who had never previously programmed or created a parametric model, were successful in designing and modelling responsive architecture with digital tools. This is not unexpected in light of the previous work by Meyboom et al (2010), Moore and Hill (2010) as well as Hu and Fox (2003), but considering the teaching approach was different, it was by no means certain.

Secondly, while the projects utilise a diverse range of inputs and produce a wide range of effects, the interaction on all of these projects is reactive and tightly scripted; if one thing happens, then a prescribed movement happens. For this reason the projects are described as responsive rather than interactive or intelligent. The responsiveness of the projects is partly attributable to the IPO diagram, which encourages reactionary behaviours in response to prescribed inputs. An approach that encourages more machine intelligence would incorporate feedback between previous interactions and states, such as was done by Ruairi Glynn in his Performative Ecologies project. However it is important to consider that digital design tools, namely parametric modelling, are not conducive to these bi-directional and history based relationships. It may be that teaching students to design more interactive architecture requires revising the IPO diagram to incorporate more sophisticated interactions, and creating a new set of tools that can model these types of behaviours.

Thirdly, on almost every project there are defined moments where the project shifted from being developed digitally to being developed physically and vice-versa. These moments were often disruptive, particularly when a student had a physical model that was difficult to capture digitally and, conversely, when a student had a digital model that left out the physical qualities of the materials - in particular material tolerances and bending. These disruptions are not necessarily negative - in many cases they encouraged more refined designs - but they do demonstrate the disjunction between the physical and digital world, and reinforce the importance of teaching students not only how to design responsive architecture digitally, but also how to prototype responsive architecture physically.

5. Conclusions and future work

For a student, learning to design responsive architecture involves technical skills like programming and parametric modelling, which they are unlikely to have encountered before. The challenge for teachers is to allow the design

process to occur concurrently, rather than separately, to the students required skill acquisition. In this research we have demonstrated that the Input-Process-Output (IPO) diagram is a useful teaching tool to guide students into thinking algorithmically before they are sufficiently skilled to create an algorithm. The draw back to this method is that it predisposes the students to creating reactionary rather than interactive architecture, although the difficulty of creating interactive architecture with the current design tools, in particular parametric models, somewhat nullifies this limitation.

The research has also demonstrated the importance of physical prototyping. At a time when design studios are increasingly held in computer laboratories, and when architecture is designed to be digitally responsive, it is important to set aside time, space and resources, so that students can learn first hand the shortcomings of their digital designs and address the physical limitations of architecture.

Our future research will involve turning the elective into a core design studio, and collaborating with the mechatronics and textile design schools to explore new materials for responsive architecture.

Acknowledgements

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PARAMETRIC MATERIALITY

Material properties as catalyst for design

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Abstract. Sustainability issues are increasingly taking more prominent positions in the hierarchy of design decisions. The combination of linked digital analysis and parametric design has emerged as an integrated method of assimilating performative characteristics into design. As these “informed design” methods evolve there is an increasing ability for architectural geometry to be rationalized, whether this is for reasons of constructive optimization, or environmental and economic justification. But the macro scale approach to geometry in design is only one mediator of the designs impact in its surroundings. This paper discusses what happens when designers fundamentally question the role of materials in design, and specifically what happens when “new” materials and their performative characteristics can be modelled and implemented into the digital design decision process. These approaches are showcased in “proof of concept” projects that have been developed using digital design and production technologies, in collaboration with material scientists and industry.

Keywords. Materiality; analysis; performance; design; fabrication

1. Introduction

Architects are continually faced with the fact that successful work is dependent on their ability to engage with a vast array of subjective, programmatic, situational and environmental variables. It is this professional setting which drives the need for architectural innovation. Within the current context, issues of performance and sustainability are becoming increasingly important; both in terms of the social and environmental responsibility of the practitioner, but also as imposed regulation in building and performance codes.

To address the increasing demands for *sustainable* design we first need to define the term specifically. For this paper we will adopt the 2005 UN definition that states that “something is sustainable if it improves the quality of human life while having a neutral or net positive effect on the carrying capacity of supporting eco-systems”. This definition is both interesting and important for architects and designers, as it shifts the emphasis of the definition onto the issue of *quality of life*, and away from the traditional and strict objective measures of energy, resource use, carbon, and pollution.

2. New justifications

In the current social, economic, and environmental context, there is an increasing requirement for sustainable buildings and urban design. Solutions for performance are becoming more and more dependent upon precision of interventions and detailed understanding of cause and effect within design proposals. However, architecture and urban design solutions typically develop in a top down manner, working from abstract representations of a problem, then, progressively detailing a solution. If a system is only understood at an abstract level, then a solution will also address only this; if a problem is understood at a detailed level, then the solution will be comprehensive. For architects to improve their own influence on the built environment, they need to understand problems and solutions at a detailed level.

The research profiled in this paper addresses this by inverting the normal progression of architectural design, to begin design at the detailed level of materiality. Our experimentation begins with a detailed understanding of a material, and then develops design suited to the material and its performative characteristics, all in relation to a project brief. To emphasize this approach the research is being conducted using “new” innovative material technologies which have multi-purpose performative characteristics.

3. New requirements

Material properties play a significant role in the decision hierarchy of all physical designs. For industries where the aim is to produce a physical product - be it a computer chip or a skyscraper - materiality and the characteristics of *matter* provide the substantive basis for physical character. As digital tools are used to search for more efficiency, performance, and greater design expression; there is an irony that materiality is re-emerging in importance.

The incorporation of *material* data into parametric design is problematic. Material value is often characterized by subjective or qualitative characteristics, and as such these values do not “fit” into the objective use of program-

ming as a design medium.

When material values can be objectively compiled in such a way as to allow for computation, scripted geometry can be used to create feedback loops that allow for optimization of specific goals. Digital analysis and evaluation scripts are increasingly being used to align materiality with digital geometry, and then with digitally controlled fabrication.

Scientific developments have invented new materials that are suitable for architecture and construction which are imbued with performative qualities. If these qualities can be integrated in digital analysis and design, then the feedback between geometry and performance characteristics becomes more complex, more detailed, and more architecturally interesting.

3. New interactions

There are three main areas of our research in which we have engaged performative material characteristics: *structural interactions*, *chemical interactions*, and *fabrication interactions*.

Structural interactions is the largest scale of material interaction, it is the combination of variable material characteristics with designed geometry. Materials are being engineered where the structural properties change based on external physical influences. Structurally adaptive materials include composites which become stiffer when exposed to vibrations, materials which become stronger when subjected to changes in temperature, or materials which become more elastic when exposed to specific noise frequencies.

Fabricative interaction materials are materials which are individually designed and then fabricated to have very specific and customized performance characteristics. Composites of this type are already used extensively in design, especially material compositions of fibres/textiles and metals/alloys. New fabricative methods for refining materials at smaller scales are increasingly being developed, and architects are already using materials that have been developed for scientific needs, only to be “re-used” for mass markets.

Chemically interactive materials are imbued with chemical or catalytic properties so as to have specifically controlled reactions with other reagents. The main realm for chemically interactive materials in architecture is in coatings, paints, and additives for concrete. Chemically interactive materials are developed to react with their surrounding environment, changing the chemical nature of their context, which in turn can influence architectural or environmental properties.

Performative materials are an interesting consideration in the design of new architecture. If it is possible to quantify the characteristics of the materials and then encode their relationships with context and geometry, then the

material qualities themselves can become drivers of parametric design.

4. New paradigms

The original source of all materials is nature. As we continue to develop new synthetic materials it is important to retain an understanding of the natural relationship between geometry and material, as often the millennia of evolution can inform us about logic and equilibrium in design.

Biological processes are inherently concerned with conservation of energy, and typically geometric adaptation is less energy intensive than the creation of new material. In most natural processes, geometry is a variable and conservation of material is the rule.



Figure 1. Windswept tree: biological reaction of growth and geometry to applied forces.

By contrast, structures designed for constructions are typically static applications of homogenous materials. Compared with their natural counterparts, synthetic material strategies appear to be less efficient; load bearing is typically achieved by adding material or changing material rather than by adapting geometry for conservation of energy.

5. New geometry

The laboratory for architectural production (lapa) has established research collaborations with material scientists, engineers, and industry. These collaborations focus on finding new and efficient architectural applications for materials, and specifically materials which have performative characteristics. The long term research goal is to develop methods in which geometry is “informed” with either material characteristics or the potentials and constraints of the fabrication processes. This approach to inform geometry is aimed at improving the sustainability, efficiency, and technical innovation in design.

5.1 ORIGAMI PAVILION

Our first project collaboration sought to develop a structure using the façade material “Alucobond” made by Alcan Composites. Alucobond is an alumin-

ium composite panel (ACP) “sandwich” material composed of thin sheets of aluminium alloy bonded to a core of polyethylene plastic. Through the composite characteristics, the material has a very strong rigidity compared with its weight to thickness ratio. The material Alucobond is not in itself new, so to retain exclusivity of the product offerings continual innovation is required to create “patentable” products. As such, the manufacturer was interested in engaging with our research lab to develop new ideas for innovation within the ACP market. To begin our collaboration, the composite material was extensively tested in our digital fabrication lab to determine structural and fabricative limits as related to our digital processing capabilities. The primary focus of this stage was to learn how to work the material, while at the same time to see how the material reacted to the forces and processes of CNC controlled tools.

5.1.1 Performative enhancements

Alcan Composites has developed a range of new “performative” coating technologies, each with chemical, structural or fabricative properties which react to external influences. Our group was presented with a list of potential performance qualities, and asked develop a project with one of them.

Our eventual choice was to experiment with the photo catalytic “anti-pollution” surface. This coating uses nanotech polymers imbedded with Titanium Oxide to coat the Alucobond. When exposed to sunlight, the coating strips Nitrous Oxide (a significant pollutant and green-house gas) out of the surrounding air and catalyzes it into harmless nitrates which are then either washed away by rain or blown off by wind¹. This same catalytic process has been used in other materials (concrete, paint, and plastics) but as it is dependent on surface area exposed to sunlight, it is particularly good for application of facades and roofing material.

The performative characteristics of this “new” material change the traditional design approach to efficiency. Typically the process of design optimization is to try to minimize the amount of material in any construct (less material = cheaper). With this performative material, however, this equation is inverted. The “environmental friendliness” of the material is directly proportional to its exposed surface area, so this means that the typical approach to material usage is inverted (more material area = better performance).

5.1.2. Parametric geometry

To make the performance concept functional requires large areas of Alucobond, however at the same time there is still an environmental cost in the high

embodied energy of aluminium. To offset this, the design was still optimized and any non-performative material in a structure was minimized. As such the design became a parametric and geometric problem: How to get the single Alucobond material to play multiple roles in the most efficient way?

Collaboration with Dr. Hani Buri from the iBois laboratory at the EPFL; – whose doctorate research investigated the efficiency of folded structures – brought the primary structural concept of “origami like” counter folding to the project. Through geometric folding of the ACM material we were able to eliminate all support structure, create large surface area spans of over 8m with a material thickness of 4mm.

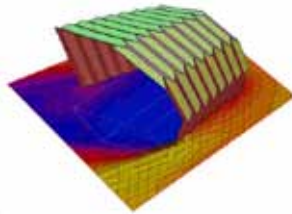


Figure2. Wind and solar analysis

The geometry of the folded shell structure also had to incorporate the need to maximize the solar exposure, so as to maximum the area photo-catalysing pollution at any one time. For best solar potential the folds needed to be balanced between being tall enough to provide structural benefit, but flat enough to minimize “self- shading” at lower sun angles.

From these design concepts, a generalized set of performance biased parametric relationships could be derived. The remaining data required to complete the contextually specific (and therefore not abstract) design was the inclusion of accurate local solar and weather data. This statistical information was used to maximize solar potential based on site specific data of solar orientation, weather, and wind. This data was compiled using Ecotect, and the script integrated spread-sheet data points to refine the folded structural geometry. The resultant script produces a folded parametric “origami” structure that can be designed for size (within material constraints) and whose geometry is responsive to site parameters and orientation.

5.1.3. Proof of concept

As a “proof of concept”, the research team and eight students constructed a small pavilion using the material with the machines in our CNC production workshop. For expediency, the resulting design for the built structure was simplified from the angular parametric geometries. In the development of the

design and construction there was a significant emphasis paid to maximizing the size of the fabricated components, minimizing the number of components, standardizing the connections, and ensuring the quality of the final joints. This was all done as a strategy for optimization of fabrication, assembly, and on-site construction time. The final pavilion was designed, prototyped, fabricated, and assembled by our students - from the paper folding to the opening party, in eight days.



Figure 3. "Performative" Alucobond pavilion

6. New scales of fabrication

The final project to be discussed is a current collaboration work, and is ongoing, so it is not being presented as a finished product, but it is rather being presented for its value in demonstrating the potential of small scale materiality and its influence at the macroscopic and structural levels of design.

6.1 ALUMINUM FOAM

Through our collaboration with materials and fabrication researchers, our team was presented with new processes of making foam metal "cores" for heat exchangers. Open cell metal foam has very efficient qualities for heat exchangers, but they have very unique appearances and sets of characteristics. The Alcan Innovation Cellⁱⁱⁱ had developed a new process for faster, more efficient, and less expensive production of aluminium foam. To offset the costs of process development, the material scientists were looking for other potential applications for the material, and as such approached our group to see if it would be of interest to designers or architects.

6.1.1 Open cell foams

The new (patented) process involves making a "moulding wafer" using a pro-

prietary pellet material, and then using high pressure injection casting of aluminium to make a solid block. The block is then opened the wafer material is dissolved, leaving behind an open cell aluminium foam.

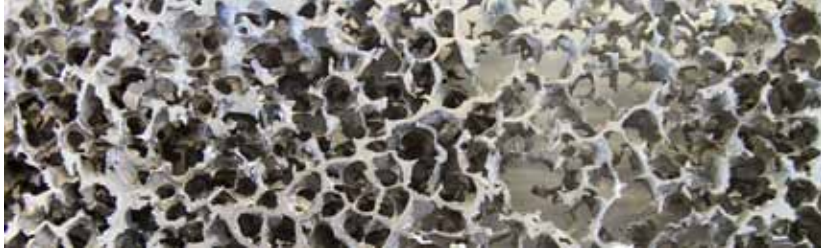


Figure 4. Detail of the parametrically variable open cell aluminium foam.

In closer analysis of the material, it was apparent that the material's structural properties are directly related to the density and patterning of voids caused by the moulding pellets. If this patterning could be organized and structured then the structural properties of the foam could be manipulated.

6.1.2. Performative enhancements

One of the “holy grails” of material design has long been to develop a material that responds precisely to the forces that are implied on it, as happens in nature, where adaptation of geometry is the prevailing method to accommodate forces. This can be seen in the growth pattern of trees (Figure 1), in the directional growth of bamboo, and also in the growth of bone (Figure 5). Localized bone density is directly related to the resistance of applied loads. This can be seen in the cross section of a human hip bone, (Figure 5) but is more radically apparent when looking at the lightweight and efficient bones of birds (Figure 6), where loading points are visibly reinforced.



Figure 5. Cross-section detail of a human hip bone.

Because of the similarity of geometry between the aluminium foam and bone, we are now conducting a research project to develop processes of creating the casting wafers such that the resulting aluminium foam can be designed to have *parametrically* defined density.



Figure 6. Cross-section a bird wing bone

6.1.3. Parametric geometry

To accomplish this the material researchers are developing their pellet casting material to have heat modulated properties, so that when cast some of the pellets shrink making smaller voids, and some of them grow making larger ones, and some of the pellets will evaporate completely leaving space for solid metal. This provides the basis for the foam organization. To physically lay and order the pellets a prototype machine being adapted 3D printing technology is being developed. The machine will “print” the variety of pellets in a programmed order, so as to “pre-set” the mould for casting. The layout, density, and mould-wafer characteristics will be determined using a combination of Finite Element Analysis software to determine the material strength locations, CAD programming to develop the pellet layout algorithms, and meshing and 3D printing software to create the NC code for the pellet deposition control.

6.1.4. Proof of concept

The current state of the project is at this early prototype stage. The research will now proceed on two levels: improving the system to control the density of material, and then developing architectural application ideas. The goal being to determine if it is possible to create efficient castings of customized structural pieces derived from digital analysis. Variable density casting holds strong potential to create customized engineered pieces with tailored structural qualities. Thus far, as the process is still in development, costing factors are not known, but it is estimated that costs will be competitive with a fully machined solid block, with advantages in minimized material waste, embodied energy, and material stresses^{vi}. This process is considered a development step in a larger investigation to produce force adaptive and dynamically performative materials. The opportunity for architects to work alongside material scientists and industry has significant promise to bring these innovations to both design and production.

7. Conclusions

The projects described in this paper are a product of design and its interaction with material scientists and engineers, but the concepts, forms, and resulting architecture has been elaborated through the use of parametric digital design software. Architects and designers continue to build their skills and talents in the realm of algorithmic and parametric design scripts, however it is important to understand that the output of these scripts need not only apply to conceptual buildings and abstract forms, but can be used to specifically relate more “abstract” contextual or performative data to geometry. As part of the definition of sustainability, the emphasis on *quality of life*, remains problematic for digital designers due to its highly subjective and non-quantitative measure. However by using the qualitative properties of new performative materials to drive a parametric design we are one step closer to engaging computational design with issues of comfort, environmental impact, and sustainability.

Endnotes

1. The conversion rate of gas to solid means that a significant amount of NiO₂ can be extracted from the air, creating a limited amount of NO₃.
2. The Alcan Innovation Cell is an on campus research office for collaboration with laboratories at the EPFL

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TREE FAÇADES

Generative Modelling with an Axial Branch Rewriting System

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Abstract. The methods and algorithms of generative modelling can be improved when representing organic structures by the study of computational models of natural processes and their application to architectural design. In this paper, we present a study of the generation of branching structures and their application to the development of façade support systems. We investigate two types of branching structures, a recursive bifurcation model and an axial tree based L-system for the generation of façades. The aim of the paper is to capture not only the form but also the underlying principles of biomimicry found in branching. This is then tested, by their application to develop experimental façade support systems. The developed algorithms implement parametric variations for façade generation based on natural tree-like branching. The benefits of such a model are: ease of structural optimization, variations of support and digital fabrication of façade components.

Keywords. Parametric Modelling; Biomimicry; Lindenmayer Systems; Branching Structures.

1. Introduction

The re-emerging science and philosophy of learning from nature is inspiring architectural design through the concept of biomimicry (Benyus, 1997). Biomimicry uses nature as a model and takes inspiration from natural forms and processes to solve human problems. The methods and algorithms of generative modelling can be improved by the study of computational models of natural processes and their application to architectural design. In this paper,

we present a study of the generation of branching structures and their potential application in the development of façade support systems.

Architects use a variety of design approaches in drawing upon nature. For example, Architektonic Architects presented a design concept for the AAC Global Headquarters in China based on the structural logic of tree growth (Figure 1, left), where the building form and structural system replicate the form of trees and branches. Toyo Ito, in his Tod's Omotesando building in Tokyo (Figure 1, centre) draws its inspiration the elm trees that line Omotesando Boulevard. Ito explains the logic as,

“Trees are organisms that stand by themselves, so their shape has an inherent structural rationality” (Pollack, 2005)

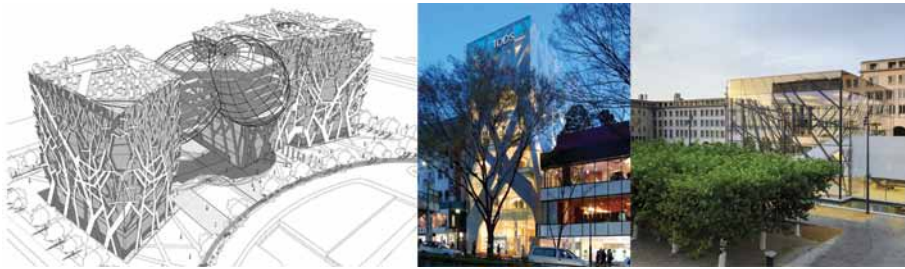


Figure 1. Examples of tree-like façades in architecture. AAC headquarters building (left), Ito's Omotesando building (centre) and A2RC's Brussels meeting centre (left).

In their entry to their Brussels Meeting Centre, A2RC Architects subdivide a glass cube with a treelike structure, gesturing to the adjacent historic garden (Figure 1, right). While these examples of architecture draw inspiration from nature but they do not utilise the formal logic of natural systems to drive the geometry. For example, in the Ito building, the form was developed in a traditional manner in partnership with structural engineer Masato Araya and his firm, OAK Structural Design Office. This paper aims to extend these informal approaches with formal generative methods to façade subdivision, driven by the logic and principles of branching systems.

2. Related work

Becker (2006) demonstrated a novel method for modelling branch connectivity with smooth nodes based on isosurfaces. Vanucci (2008) developed the notion of pluri-potential branching systems based on the interaction between biological processes and computation. Architectural applications of branching structures drawing on biological processes, computation and architectural design are explored in his research. Greenberg (2008) outlined the mathe-

mathematical logic underlying various types of branching systems found in nature. Serrato-Combe (2005) investigated the application of Lindenmayer Systems in architectural design.

3. Branching structures

Branching structures are a dominant occurrence in natural structures, such as trees and rivers. They have been investigated in mathematics and computer science as efficient data structures for search algorithms (Bovill, 1996). In design, novel studies of route networks, structural systems and spatial organisation have also touched upon the concept of branching (Frazer, 1995; Panchuk, 2006). They have been proven to be an optimised form of creating node-edge networks. In this paper, we present the application of two types of branching algorithms to develop façade support systems, a simple recursive bifurcation algorithm (Figure 2) and a rewriting system based on L-systems (Figure 3).



Figure 2. Bifurcation with recursive subdivision with depth $d = 1, 2$ and 6 .

3.1. RECURSIVE BIFURCATION

Bifurcation is the process of division of a main body into two parts or branches. This, when replicated, allows for the development of a simple branching system. This system is based off a single starting line that recursively generates new lines at the endpoint of the parent line. This allows for infinite branching and therefore requires careful control of the recursion depth. The control of the angle of division allows for the exploration of the geometric generation.

3.2. REWRITING SYSTEMS

Rewriting systems are a powerful method of generative modelling in design. Using a set of rules or productions, they allow for the parts of a simple initial object to be successively replaced resulting in a more complex final object.

String re-writing systems were first formally defined at the beginning of the 20th century by Thue, a Norwegian mathematician. String rewriting gained wide interest in the late 1950's due to Chomsky's work on formal grammars. At the centre of attention were sets of strings, called formal languages, and the methods for generating, recognizing and transforming them. These systems became critical to the development of computer languages.

In 1968 Aristid Lindenmayer, a biologist, introduced a new type of string-rewriting mechanism as a theoretical frame work for studying the development of simple multi-cellular organisms, and subsequently was applied to higher order plants. This type of string re-writing mechanism is termed an L-System and is based on the central concept of rewriting (Przemyslaw et al, 1990). L-systems provide a mathematical description of tree-like shapes and methods of generating them.

The key difference between Chomsky's grammars and L-systems lies in the method of applying productions. In Chomsky grammars productions are applied sequentially, while in L-systems they are applied in parallel and simultaneously replace all letters in a given word. This difference reflects the biological motivation of L-systems, with the productions intended to capture cell divisions (Prusinkiewicz and Lindenmayer, 1990).



Figure 3. L-system based rewriting system with depth $d = 2, 4$ and 6

4. Recursive bifurcation model

The standard model of recursive bifurcation, explained in Section 3.1, takes an initial line and places two copies of it at its end point. These copies are rotated by a rotation parameter with a positive and a negative phrasing to allow for a left and right branch generation. This process is then repeated on each of the new branches until the depth of the recursion is met. Recursive bifurcation was implemented within Generative Components with two extensions, the rotation and scaling variables were parameterised and randomised.

The rotation angle was modified by replacing the branching angle input with a random generator. Within this random angle generator, limits were set to ensure that the differences between branches were not too extreme (Figure 4, Left). As a result the script generates a completely different tree form each time the script is run. The second modification was to introduce a variable scaling input, which adjusts the length of the copied line by a variable scale factor. (Figure 4, Right).

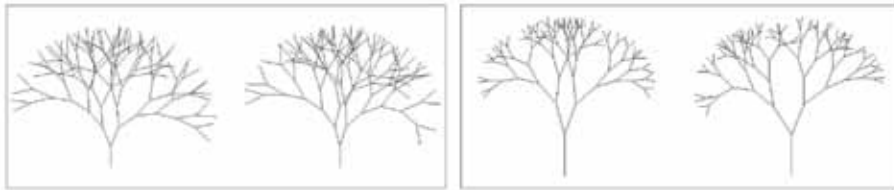


Figure 4. Bifurcation system with random angle (Left) and variable scale factor (Right).

While our bifurcation script allows for the generation of a tree pattern, it lacks any boundary definitions that can relate it to a building. If the tree is maintained within the façade boundaries, problem areas arise were the tree falls short of the boundaries. This is solved by ensuring that the tree is larger than the surface area required and the designer can then manually determine which section of the tree pattern will be used (Figure 5).

The bifurcation model successfully subdivides a façade while providing a tree like pattern. While this model offers advantages over manually drawing the subdivision, both in the variation within and the speed at which different options can be generated, it is still limited to the simple use of bifurcation. To implement deeper logic within tree branching, we have developed a rewriting script based on L-Systems.

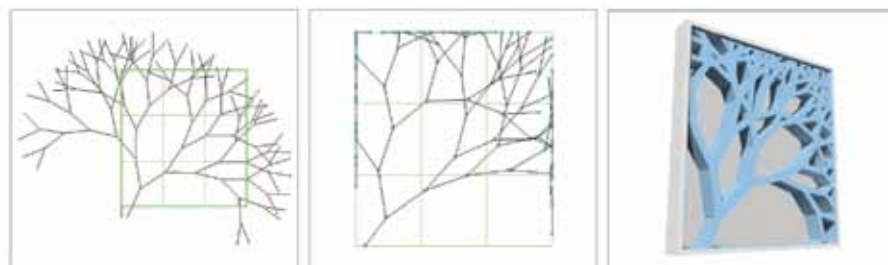


Figure 5. Boundary area (Left) and projection (Middle), final Façade model (Right).

5. Rewriting system model

In order to address the limitations of the recursive model outlined above, a second method of branch generation was investigated. In this scheme, a façade model based on L-systems was developed.

5.1. DOL SYSTEM

The simplest class of L-systems are those that are deterministic and context-free, called DOL-systems. A DOL-system is defined as the ordered triple $G = (V, w, P)$, where:

- $V = \{s_1, s_2, \dots, s_n\}$ is an alphabet composed of a set of distinct symbols.
- w , known as the axiom
- P , known as the finite set of productions

In order to understand how they work consider a string built of two letters a and b . Each letter is associated with a rewriting rule, in this example $a \rightarrow ab$ and $b \rightarrow a$. This means that the letter a is replaced by the string ab and the letter b is replaced by a .

The rewriting process begins from a distinguished string called the axiom in this case a . In the first derivation step the axiom a is replaced by ab . The word ab consists of two letters, so in the second step both are simultaneously replaced, a with ab and b with a resulting in the string aba . In a similar manner the string aba results in $abaab$, which results in $abaababa$, and so on (Figure 6, Left).

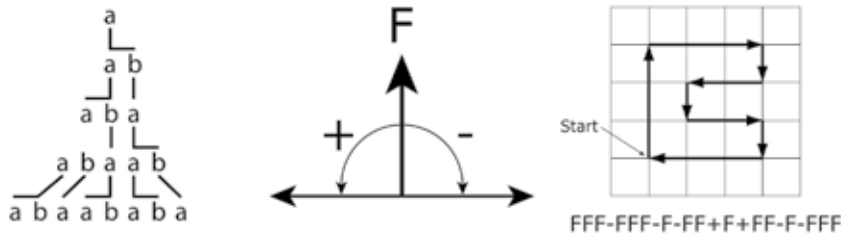


Figure 6. D-OL System (Left), Turtle Interpretation of string symbols (Middle) and Interpretation of a string (Right).

5.2. TURTLE INTERPRETATION

An L-system in its own right only provides a string and in order to develop the string into geometry we require a turtle. A turtle is a historical term that comes from the early days of computer graphics, where a mechanical robot turtle, capable of simple movement and carrying a pen, would respond to instruc-

tions (McCormack, 2008). The string is the instructions that are interpreted by the turtle as movement, orientation and geometry building actions. Reading the string from left to right the turtle interprets specific symbols responding accordingly (Figure 6, Middle), and given a step size and angle increment the turtle responds to commands represented by the following symbols:

- F Move forward a step of length d.
- + Turn left by angle δ . (Orientation of angles is counter clockwise)
- - Turn right by angle δ .

The turtle interprets a character string as a sequence of line segments and depending on the segments lengths and the angles between them, the resulting line from the turtle can be self-intersecting and more or less convoluted. The line always remains a single line, but can have some segments drawn many times (Figure 6, Right).

5.3. FAÇADE SUBDIVISION

A DOL-system for façade subdivision was developed with the following parameters:

- $V = \{F, X, +, -, [,]\}$
- $w : X$
- $p1 : X \rightarrow F[-X]F[+X]-X$
- $p2 : F \rightarrow FF$

This generates the sequence of words, where n is the derivation length = the number of iterations:

- w = $n_0 = X$
- n_1 = $F[-X]F[+X]-X$
- n_2 = $FF[-F[-X]F[+X]-X]FF[+F[-X]F[+X]-X]-F[X]F[+X]-X$
- n_3 = $FFFF[-FF[-F[-X]F[+X]-X]FF[+F[-X]F[+X]-X]-F[-X]F[+X]-X]$
 $FFFF[+FF[-F[-X]F[+X]-X]FF[+F[-X]F[+X]-X]-F[-X]F[+X]-X]-FF[-F[-X]F[+X]-X]FF[+F[-X]F[+X]-X]-F[X]F[+X]-X$

This demonstrates how the size of the string increases rapidly. This system was run until $n=7$ to develop a string comprising of 13,956 characters to input to the turtle. The turtle, described previously, interprets the string as a sequence of line segments. What is slightly different about this particular string is that X is a placeholder and is used to nest other symbols, and has no effect on the turtle. With the string input to the turtle additional inputs are required, the length of the line segment and the angle increment of the turtle when rotating. In this particular case a line segment length of 500mm is used and an angle increment of 22 degrees. This results in an L-system based tree being drawn,

which while providing the desired overall geometry present areas for further development.

While the L-system model offers a more natural looking tree, the fixed angle increment results in a sense of regularity within the branching of the tree; similar to the bifurcation model. With this in mind, a new turtle was developed that is able to take a minimum and maximum angle increment input. Using this range the turtle is able to generate a new angle increment value each time that it reads a – or + from that string, resulting in a more varied tree generation due to the variation in the angle increments (Figure 7).



Figure 7. Initial L-system Tree (Left), examples of random angle increment (Middle, Right)

While the random input to the angle increment offers more variety in the tree generation, of more concern is the method in which the standard turtle draws the L-system. Because the turtle interprets the string as individual line segments of a fixed distance the total count of line segments is rather high, in the current example the turtle produces 4118 individual line segments. While this might not be an issue in terms of the visual aspect of the drawing it presents problems if further development and analysis is to be undertaken. In order to simplify the tree the new turtle was developed to simplify the string as it reads it. This is achieved by the turtle looking at the next character as it reads the string:

- If character = F, then advance the count.
- If character = [, then commit new line and start again.

As a result the turtle multiplies the F count by the line segment length input and draws the simplified line, when it reaches a [in the string it begins again. This results in the line segment count being drastically reduced, in the current example dropping from 4118 to 2186 (Figure 8).

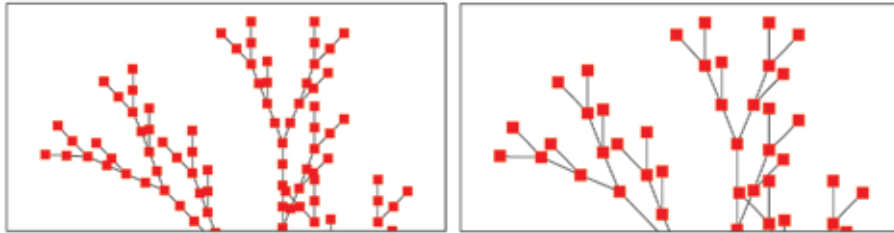


Figure 8. Line simplification before (Left) and after (right).

The required surface area is positioned in the desired section, with the tree geometry then being projected onto the surface (Figure 9). This allows for the surface to be sub-divided into lines of structure and areas of infill panels.

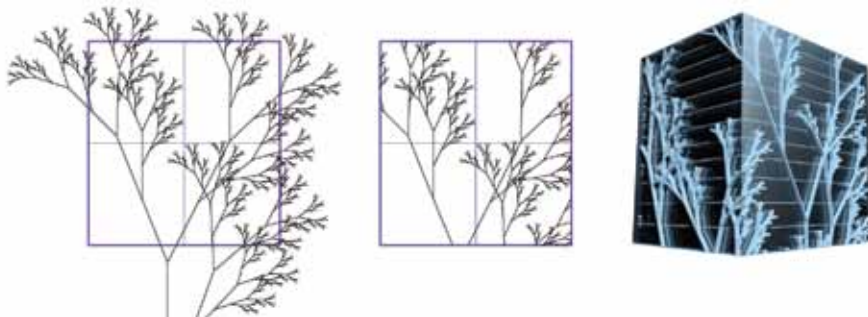


Figure 9. Overall L-system tree (Left) and projection (Middle), final Façade model (Right).

6. Results

This paper demonstrates the generation of façade support systems based on two models of branching, namely recursive bifurcation and L-systems. These two types of branching algorithms are implemented as parametric scripts for façade generation based on natural tree-like branching. We extended the standard procedures for branching variation by employing a randomised rotation operator and a parameterised scaling factor. Further, we introduce a boundary condition operator that permits the mapping of the branching script output to simple façade subdivision. The façade support systems generated by our branching scripts captures not only the form but also the underlying principles of biomimicry found in branching.

While the focus of this paper was to generate plausible branching struc-

tures for application to façade support systems, it is limited to two dimensional branching. Our goal is to extend the algorithms to three dimensional branching and to develop efficient and optimised subdivision algorithms that can be scaled to real world design. We intend to extend this research to employ structural optimisation methods to test the feasibility of our generated models in terms of structural support and material constraints. The benefits of such a model will be further tested in future research for ease of structural optimization, variations of support and digital fabrication of façade components.

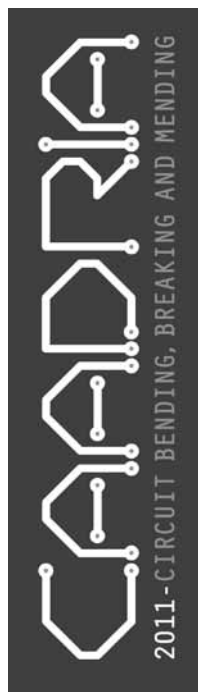
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VIRTUAL AND INTERACTIVE ENVIRONMENTS



VIRTUAL AND INTERACTIVE ENVIRONMENTS I

18.	Understanding and constructing shared spaces for supporting informal interaction at a distance	189
	<i>Thi Lan Truc Nguyen and Beng-Kiang Tan</i>	
19.	A context immersion of mixed reality at a new stage	199
	<i>Juhyun Lee and Mijeong Kim</i>	
20.	Three-dimensional computational structures and the real world	209
	<i>Werner Lonsing and Peter Anders</i>	
21.	Real time modelling: A solution for accurate, updatable and real-time 3D modelling of as-built architecture	219
	<i>Russell Lowe, Jules Cromarty and Richard Goodwin</i>	
22.	Real-time porosity: Combining a computer game engine with environmental sensors to better understand pedestrian movement in public/private space and in real-time	229
	<i>Russell Lowe, Mark Hedley and Richard Goodwin</i>	

UNDERSTANDING AND CONSTRUCTING SHARED SPACES FOR SUPPORTING INFORMAL INTERACTION AT A DISTANCE

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Abstract. This paper discusses the support of informal interaction at a distance using shared space approach. From examining existing examples, we identified critical issues and suggested that a lack of sense of shared space might be the cause of these issues. In order to understand how sense of shared space is supported in these systems, this paper introduces a taxonomy of mediated shared space for informal interaction whose categories are classified based on the degree to which the sense of shared space is supported.

Keywords. Informal interaction; shared space; collaborative virtual environment.

1. Introduction

Informal interaction such as having a short conversation after encounter in hallway, chatting after the meeting, gossiping during break time is acknowledged to be an important factor in organizational outcomes (Mackay, 1999; Isaacs et al, 1997). When people are co-located or together in a single building, physical proximity increases the probability of frequent encounters among them thus they can maintain their casual conversations day by day. Nowadays, collaborative works are widespread with geographically distributed teams and co-workers. With such physical distance, informal interaction among team members is unable to occur as usual. In order to maintain the benefit of informal interaction, researchers have developed a variety of methods which employ video-based technologies, virtual reality technologies, locator technologies, ubiquitous technologies, etc. to enable

informal interaction among geographically distributed people. Although these technologies have provided essential mechanisms conducive for informal interaction to take place naturally, some problems are still reported.

This paper is interested in the cause of the problems and how to address them. First, we examine research projects developed for supporting informal interaction at a distance and the major issues that emerged from these systems. Second, we identify the causes from which the problems are actually rooted by analyzing the problems based on some grounded literature. We suggest that, the problems of these systems are caused by lacking a sense of shared space. Thirdly, we re-examine and categorize technical methods for supporting informal interaction at a distance towards shared space approach. A taxonomy of mediated shared space for informal interaction is introduced whose categories are classified based on the degree to which the sense of shared space is supported. This work helps to have a better understanding of how the sense of shared space is supported by corresponding technologies and can be a reference to develop new approaches based on the characteristics of each category.

2. Informal interaction at a distance and its issues

2.1. DEFINITION

Kraut et al (1990) defined informal interaction as “conversations take place at the time, with the participants, and about the topics at hand.” Based on the way in which people interact, E.Campbell and A.Campbell (1988) defined informal communication as “relatively unstructured information exchanges that tend to occur in face-to-face encounters during “off-task” moments.” In general, informal interaction is spontaneous and often occurs by chance when people encounter each other. The conversation could be unintended (spontaneous and opportunistic interaction) or intended based on the initiator but it is not scheduled in advance by both parties.

2.2. SUPPORTING INFORMAL INTERACTION AT A DISTANCE

When people are scattered at geographically distributed locations, physical distance disables the opportunities for chance encounter among them thus their interaction are totally mediated by technologies. General communication technologies facilitating this need include telephone, video conferencing, instant messaging and voice chat (Skype). However, it has been reported that in using these technologies, communication is less frequent, sometimes delayed in sending and receiving messages, and more effortful (Kraut et

al, 2002; Mackay, 1999). Above all others, these systems do not provide informal information such as peripheral awareness, chance encounter with which people are encouraged to come into contact and communicate. In order to maintain the benefit of informal interaction when people are physically separated, researchers have developed a variety of ways in order to imitate the actual situations for informal interaction to occur. They are:

Video-based Technologies. In general, video-based technologies make use of audio-video channel to be aware of people's presence and the degree to which people are available for communication; and to mimic face-to-face communication. In particular, each application employs different mechanism to facilitate informal interaction in its own way. For example VideoWindow (Fish et al, 1990) used video connection as a shared window for informal communication between two public lounges; Cruiser (Root, 1988) and Montage (Tang and Rua, 1994) employed the notion of "walking through a hallway and glance into open offices to see who was there" in which the virtual hallway is actually a path that contains a set of locations (offices, common areas, etc.) which the user might visit. RAVE (Gaver et al, 1992), Portholes (Dourish and Bly, 1992) and OfficeWalker (Obata and Sasaki, 1998) employed overview model to create "virtual shared offices" where people can keep a peripheral awareness of people and activities in a variety of places indefinitely through a matrix of slowly scanned continuous video images.

3D Virtual Reality Technologies. 3D Virtual reality technologies make use of 3D multi-users virtual environments or 3D collaborative virtual environments (CVEs) as shared virtual environments for geographically distributed people to socialize, interact and communicate. Each user is represented in terms of an avatar and able to populate, navigate and interact with others within a virtual environment. Typical 3D environments include Contact Space (Phillip and Andrew, 2000), FreeWalk (Nakanishi et al, 1998) and Valentine (Honda et al, 1999).

Locator Technologies. Locator technologies make use of positioning trackers such as active badges to track the staff's current location information in realtime (Want et al, 1992). A typical application of locator technologies for informal interaction is ActiveMap in which images of people's faces are superimposed over their latest tracked positions on the 2D map thus help people to engage in more intended interactions (McCarthy and Meidel, 1999).

Ubiquitous Media. Ubiquitous media takes the notion of media spaces one step further in which technologies are invisible and integrated into general ecology of workplace. Ambient Agoras (Streitz et al, 2007) is a smart environment which is developed to support awareness for informal communication, coordination and collaboration among distributed teams. It

uses the notion of ambient display and lightweight awareness mobile device for creating environment populated artifacts. The environment contains three artifacts: Personal Aura, Hello.Wall and View Port. Personal Aura is a mobile artifact for controlling user's appearance such as visibility or social role (project manager, regular member, etc.) in the remote environment. Hello.Wall is a 2D ambient display wall in which light patterns are used to display mood, activities, presence and interest of the remote teams. And View Port is a personal mobile device which is used to display personal information that is shown and stored in the Hello.Wall.

2.3. CRITICAL ISSUES OF THESE SYSTEMS

In daily life, informal interaction often occurs in two phases in turn: *awareness then engagement*. In other words, before people engage in a conversation, they must be aware of each other's presence and availability. Research projects have imitated the two phases in their systems for supporting informal interaction at a distance, however, critical issues also emerged from the two phases because of the nature of the supporting technologies. Two typical issues are: privacy violations and intrusiveness; and lack of engagement.

Privacy violations and intrusiveness concern the level of control to which people are accessed by others. Experimental results of Cruiser revealed that the method for initiating communication was abrupt and intrusive. The "glancing to other office" feature for being aware of other's availability caused a sudden image of the caller on the recipient's screen, thus, it might violate recipient's privacy and interrupt his/her current activities (Obata and Sasaki, 1998). Moreover, the caller's image placed the recipient in the zone for conversation (50cm-150cm) (Nishide, 1985) that urged the recipient to respond even when it was not welcome. Privacy violations and intrusiveness were also found in CVEs such as FreeWalk when an individual barged into a group of people talking among themselves.

Lack of engagement concerns the low possibility of an encounter leading to communication. Evaluation on the use of video-based technologies reports that spontaneous interactions did occur across these video connections, however, they occurred less frequently than in actual situation where people spontaneously encounter each other in a physical environment. The probability that an encounter will lead to communication is therefore reduced (Fish et al, 1992). Similarly, spontaneous encounter also occurred in CVEs environment while participants were moving. However, occurrence of conversation in 3D space was scarce since participants enjoyed moving in 3D virtual space more (Nakanishi et al, 1998). Lack of engagement is also reported in the evaluation of the Hello.Wall artefact. Although Hello.Wall used abstract patterns

for illustrating presence and awareness of remote team in order to reduce distractions and privacy concerns, the artefact did not attract any attention of people who were not the research participants although they were around the Hello.Wall.

2.4. SHARED SPACE APPROACH

According to Gaver (1992), shared space is described as an “encompassing space” which “is rich with perceptual information about objects and events that can be explored and manipulated”. By being co-located or being together in a shared space, people are able to encounter each other frequently thus the repeated encounters may lead to communication (Kraut et al, 2002). Additionally, spatial frame pushes people into a mutual recognition zone (Nishide, 1985) by which people are able to be aware of others’ presence and availability before approaching them for a conversation. Also, the space designated for informal communication such as cafeteria, break area may attract and hold people together in one location thus extend the opportunity for them to interact (Fayard and Weeks, 2007).

To account for the issues in 2.3, “mediated interactions between people via technology are prone to breakdown due to inadequate feedback about what information one is broadcasting and ability to control one’s accessibility to others” (Bellotti et al 1993). Obata and Sasaki (1998) claimed that such breakdown also occurs due to “a lacking sense of distance” among users in the network so that people are urged to respond to the conversation at a close distance and cannot ignore it. In conjunction with this criticism, Kraut et al (2002) shown that interruption and loss of privacy in video-based systems are due to the metaphor of physical proximity for initiating communication that sometimes caused unwelcome conversations. We suggest that the problems in section 2.3 occur due to lack of the actual sense of shared space for informal interaction.

3. Taxonomy of mediated shared spaces for informal interaction

This section examines and categorizes technical methods for supporting informal interaction at a distance towards shared space approach. From this categorization, we locate four major categories according to the degree to which the sense of shared space is supported. There are two motivations behind this classification. First, it helps to understand the degree for supporting shared space and the degree of corresponding technologies for supporting informal interaction so that others could utilize appropriate type of mediated shared space and supporting technologies for their research purpose. Second,

it allows us to identify the gaps emerging from each type of shared space thus enables new spatial approach to develop based on these gaps.

3.1. TAXONOMY BASED ON TECHNICAL METHODS

There are two typical categories of shared space in this taxonomy - shared physical spaces and shared virtual spaces (Figure 1).

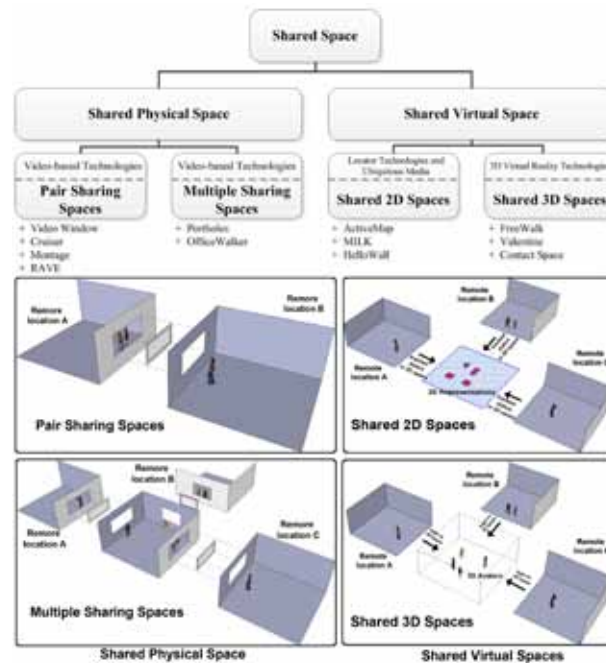


Figure 1: Taxonomy of shared spaces based on technical methods for informal interaction

Shared Physical Spaces. The shared spaces are created by using video-based technologies to connect two or more physical spaces in which one or more cameras are used to capture the scene of one location and display it on a screen located at other remote location. In this way, people in one physical space can view another physical space through a video screen in real-time. The video screen acts as a window to share the real scene between the two separate spaces so that inhabitants of these spaces will have the feeling that the other remote space is just behind the screen. The video screen could be a large screen such as projection screen or large TV, a desktop screen or even a handphone screen. People are able to communicate in face-to-face manner through the screen and serendipitous encounter may happen when people take a glance over the screen and is aware of someone's availability at the other

side. The larger the screen the more sense of shared space is supported since a very wide image can convey a heightened sense of realism (Fish et al, 1990). Since people can use one or more screens to connect with one or multiple remote locations at the same time, thus, the shared-physical-spaces category could be divided into two sub categories: pair sharing spaces and multiple sharing spaces. Pair sharing space is created by establishing video connection between two physical spaces. It can be used for private communication if the two physical spaces are individual's office spaces. Typical examples of pair sharing spaces are RAVE, VideoWindow, Cruiser and Montage. Multiple sharing spaces are created by establishing video connection between one physical space to many physical spaces. In this way, one physical environment shares its space with many other physical environments and vice versa. Typical examples of multiple sharing spaces are Portholes and OfficeWalker.

Shared Virtual Spaces. The shared spaces are created by enabling geographically distributed people to populate in a multi-users virtual environment. Each user has his/her embodiment representing for his/her presence in the environment. E.g. users of Contact Space and Valentine are represented as graphical avatars; FreeWalk users are represented as moveable pyramids embedded with real-time video of user's face on one side of the pyramid; users of ActiveMap and MILK are represented by the real photo of his/her face placed at his/her current position on the 2D office layout; and in Hello.Wall users are represented as individual patterns. We can group these shared virtual spaces into shared 2D and 3D spaces. In the shared 2D spaces, users' embodiments are displayed on a 2D surface such as an office layout or a designed surface in which the information of users' current location and availability for communication are provided for intended informal communication. Typical examples of 2D surface spaces are ActiveMap, Hello.Wall, and MILK. In the shared 3D spaces, geographically distributed people share a 3D virtual environment which supports spatial cues and structure, enabling people to navigate and interact naturally. Representative examples of shared 3D spaces are Contact Space, FreeWalk and Valentine.

3.2. CLASSIFICATION OF SHARED SPACES ACCORDING TO PERIPHERAL AWARENESS AND INTERACTIONAL POSSIBILITY

By being in a shared environment people can be mutually aware of their surroundings (peripheral awareness) such as what is going on, "who is around, what sorts of things they are doing, whether they are relatively busy or can be engaged" (Gaver, 1992). Upon the availability of people, one could approach and interact with his/her counterparts (interactional possibility). Therefore, we locate the four categories according to two dimensions -- the degree of

supporting “peripheral awareness” and the degree of supporting “interactional possibility” (Figure 2).

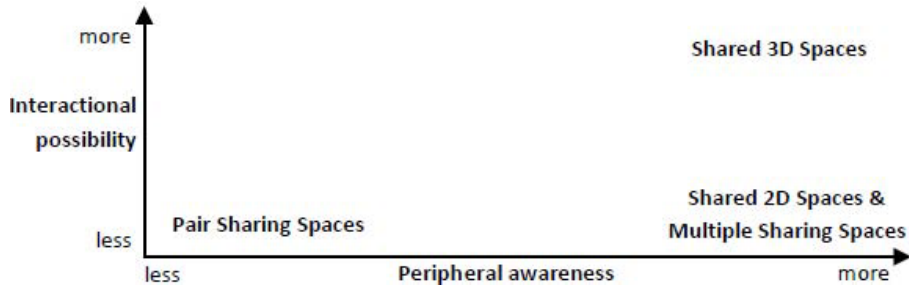


Figure 2: Classification of shared spaces for informal interaction according to the degree of shared space

Peripheral awareness. This dimension concerns the degree of being together in a shared environment through the opportunities to see and be aware of presence and availability of people who are geographically distributed in a non-obstructive way. In pair sharing spaces, peripheral awareness is less supported since the connection is only supported for two physical spaces. Moreover, the shared scene is restricted by camera range thus whatever out of the camera frame is unable to be seen. E.g. although VideoWindow provides a big screen to allow nearly the whole lounge area to be seen together with people thus support a great sense of shared space between the two remote lounges, however, some people often tried to strike up the conversation by moving close to the screen. It caused their head to move out of the camera range thus they could not be recognized by people at the other side (Kraut et al, 1990). With multiple video connections, multiple sharing spaces support a better peripheral awareness among people in various places through multiple screens. Similarly, the information in a shared 2D surface supports awareness at a glance through the information of presence, location and availability status of different people.

Interactional possibility. This dimension concerns the degree of being together in a shared environment through the possibility of approaching, participating and interacting or ignoring a meeting in the shared environment. Video-based technologies support interaction by providing “always open” audio-video link for quick interaction. However, evaluation of these systems showed that interaction occurred only among those who are already connected. Others are unable to join existing connections since there was no way to interrupt or override the existing links (Isaacs et al, 1997). Therefore, the categories of pair sharing spaces and multiple sharing spaces are placed

towards supporting less interaction. Similarly, although the shared 2D spaces are obvious and intuitive to indicate the updated information of people for intended interaction, interaction may not occur since people do not wish to wear the location tracker due to privacy issue (Carlsson and Hagsand, 1993). Interaction possibility is well supported in 3D virtual reality technologies since participants are able to freely populate, navigate, and communicate as well as socialize in one virtual spatial frame using real world metaphors.

4. Conclusion

This paper has discussed supporting informal interaction at a distance, a way towards shared space approach. We have introduced a taxonomy of mediated share spaces based on the existing technological approaches, for an understanding of the degree for supporting shared space and the degree for supporting informal interaction of these technologies. It is our hope that this taxonomy would be useful for research works which require a sense of shared space for informal interaction. Although this classification is for informal interaction, it could be suitable for any collaboration-at-a-distance purposes. Though in figure 2, shared 3D space is classified as an ideal shared space that meets the requirement of peripheral awareness and interaction possibility, interaction in shared 3D space is meaningful only if virtual workers are around and involved in the activities of the virtual world. Since virtual workers are not logged onto the virtual world all the time, thus, to some extent, the likelihood for informal interaction to occur in CVEs is not as high as in real life where their co-workers are around and can easily engage in a conversation when they encounter each other. Therefore, in our next stage of work, we will develop a model of shared physical-virtual spaces in which the integration of physical and virtual environment will overcome this limitation.

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A CONTEXT IMMERSION OF MIXED REALITY AT A NEW STAGE

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Abstract. This paper presents a novel approach to the potential of mixed reality embodied in smart phones and ubiquitous environments. We analyzed the related works to the concept of context and mobile computing and then investigated into leading companies by interviewing senior managers of the mixed reality (MR) projects in Korea. As a result, the concept of context immersion is proposed for describing the various context relationships among the real locations, objects and persons. By considering the MR environments as a converged world, this paper characterizes the context immersion as the combination of the time and location-based, object-based and user-based contexts. Through the context immersion, users can be connected to the real life, not limited to the imagery world, thus experiencing strong immersion in the MR environments. At the end, we present the development direction for the future with a focus on the MR contents rather than the technical aspects.

Keywords. Context Immersion; Mixed Reality; Augmented Reality; Ubiquitous Computing; Mobile Computing.

1. Introduction

As new devices in ubiquitous computing such as smart phones and appliances have been much developed, the mixed reality (MR) has become one of emerging issues in all areas of our daily life. Mixed reality (MR) commonly overlaps computer-generated images and real images in the physical world. Recently, research on MR has adopted a new approach focusing on humanities and social sciences, where the MR combines real environment with geometric information as well as user and social network information. From the point of view, this study will propose the concept of context immersion at a

new stage for explaining the new paradigm driven by the smart phones and ubiquitous computing in MR. Instead of a head-mounted display (HMD) that Sutherland (1968) presented as a see-through display, MR has become to adopt ultra mobile smart phones and PDAs (Wagner and Schmalstieg, 2009). Our research starts from the potential of the smart phones that allow powerful networking and mobility. Smart phones realized the seamless MR as a personal media hub.

2. Background

2.1. MIXED REALITY AND SMART PHONE

Many works on MR have discussed the combination of the real and virtual as well as real time interaction and registration in 3D since Azuma's survey (Azuma, 1997). However, not only text and 2D information but also various media beyond 3D images have been used in the domain of the MR. Milgram (1994) illustrated MR as a virtuality continuum that consists of augmented reality (AR) and augmented virtuality (AV). Since our work starts at the context in the real environment, we focus on the AR more than AV considering the concept of immersion in virtual reality (VR).

For the common usage of the AR, Azuma et al (2001) presented nine areas as fundamental elements to be developed: Ubiquitous tracking and system portability, Ease of setup and use, Broader sensing capabilities, Interface and visualization paradigms, Proven applications, User studies and perception issues, Photorealistic and advanced rendering, AR in all senses, and Social acceptance. The MR domain has dealt with smart phones and ubiquitous computing, thus smart phones become an ideal platform for MR (Henrysson et al, 2005).

2.2. CONTEXT AWARE

Ishii and Ullmer (1997) coined the term 'tangible bit' that represents interactive surfaces, coupling of bits and atoms, and ambient media. The concept of mixing the real and virtual can be found in the ubiquitous computing environments, where the real is an electronic world that responds to the cyber space. The MR visual interaction can be one of the ubiquitous computing environments. Many works have dealt with the context to understand the ubiquitous computing environments.

Schilit (1994) explained that the context is to consider the endless changing environment. Liberman (2000) defined that context is everything except the explicit input and output. Gellersen et al (2002) described that the context

is captured through sensors and defined by analyzing sensor data. Dey (2000) suggested the context to be any information which characterizes the situation of an entity. For the context types, location, identity, time, and activity are considered. The context can be used for context aware mobile devices such as smart phones and PDAs. To understand our environment effectively, context awareness adopts the reasoning method of 5W1H (Schilit, 1994; Dey, 2000; Ha et al, 2006).

The related AR works (Pyssysalo et al, 2000; Priyantha et al, 2001; Herrysson and Ollila, 2004) considering mainly ubiquitous computing and context awareness deal with location-based systems. Location is the most basic context in the ubiquitous environments. Smart phones detect the location using a GPS receiver, compass and accelerometer. Of course, they have a sensitive camera and a bright display like AMOLED. Abowd et al (2005) argued that the smart phone is the most powerful platform for pervasive computing.

2.3. IMMERSION

Slater and Wilbur (1997) defined immersion as a description of display technology that can be objectively assessed in terms of stimuli from reality, sensory modalities, a field of view and a display resolution. However, Witmer and Singer (1998) described the concept of immersion as a psychological state of being enveloped by and interacting with an environment that allows users a continuous stream of experiences. The former emphasize the technology itself that delivers the immersion to users whereas the latter deals with the users' feelings immersed in the system. This research adopts the latter definition of immersion for introducing a context immersion of MR for smart phones since our focus is on the users' experience in MR environments implemented by mobile and ubiquitous computing.

Until now, research on immersion mainly has dealt with immersive virtual environments (VE) where the users are surrounded by sensory interfaces and then perceptually feeling of being in the virtual worlds (Carrozzino, 2010). The conventional immersive VEs have been achieved by developing wearable devices and large displays that isolate the users completely from the real context. One of the wearable devices to embody the immersive VE is head mounted displays (HMDs) that confine the user's view in the simulated environment. Kuchelmeister et al (2009) proposed an immersive AR system, 'iDome', that provides panoramic and spherical representations for visualization. The immersive VE called NICE was implemented in a highly graphical immersive VR system called the CAVE (Cruz-Neir et al, 1993). Smart phones do not provide such large scale of displays or surrounding interfaces, but enables seamless interaction between the real and virtual domains in MR.

3. Exploratory research

3.1. LITERATURE STUDIES

The related works on 'mixed reality' were searched through the article titles, abstracts, and keywords in SCOPUS online database. The total number of articles including journals conference proceedings is 1975. Most of the articles belong to the subject area of Computer Science and Engineer (50.5%). The result of our studies that categorized the articles by keywords is coincided with that of the survey made by Zhou et al (2008). Zhou and his colleges presented research trends in AR with a focus on tracking, interaction and display. They classified the papers of ISMAR proceedings into two groups. The first group includes five main research topics associated with technical issues: Tracking techniques, Interaction techniques, Calibration and registration, AR applications, and Display techniques. The second group is composed of more emerging research topics: Evaluation/testing, Mobile/wearable AR, AR authoring, Visualization, Multimodal AR, and Rendering. These issues would be more related to our research topic since mobile AR and human immersion will be discussed in this paper.

When the articles are classified by the source title, the proceeding of International Symposium on Symposium on Mixed and Augmented Reality (ISMAR) is dominant. Since 2009, ISMAR has included the section of an art, media, and humanities (AM&H) in the science and technology (S&T) part. The articles in the AM&H proceedings have given us the inspiration of context immersion in smart phones. Many of workshops, exhibitions, and installations in the conference have dealt with smart phones. ISMAR 2010 was in the same situation. Stapleton and Rolland (2010) expected that the exploration of the AM&H would be a dominant scope for the future since MR is based on more ubiquitous and mobile computing.

In the AM&H proceedings of ISMAR 2009, the augmented view of Dashuifa (Yetao et al, 2009) described 3D images that were restored through a telescope at the historic sites. Mission Dolores situated simulation (Liestol, 2009) showed a customized education and tourism contents using smart phones. Loosely coupled mixed reality (Myungho and Kim, 2009) used the environment metaphorically to combine the virtual and real using smart phones. EYEPLY (Hurwitz and Jeffs, 2009) in a smart phone provided the marketing and promotion as commercial services for users at the stadiums, parks, conventions and shopping malls. SLARiPS (Second Life Augmented Reality in Physical Space) Project (Stadon, 2009) showed avatars, 3D online platform and the process of MR considering cultural aspects. Koh et al (2010) suggested

a mobile AR cooking game with a focus on user interfaces and interaction from 2D to 3D spaces. Hertz et al (2010) developed an AR arcade driving game using GPS navigation and MR seamlessness. These articles present a variety of views on MR but all of them deal with a seamless context in the real environment. Also, according to the point of view, each paper focused on specific contexts among the various contexts such as location, identity, time, user, and object.

3.2. MIXED REALITY PROJECTS IN KOREA

We investigated leading MR companies in Korea and interviewed managers who plan their MR projects. Many of them have developed MR applications with smart phones. The MR applications are classified into three groups in terms of immersion. The one is to overlay virtual images over the real camera screen. The others are location-based applications such as Wikitude and Layar. The third is identified as social network service (SNS).

The simple overlay applications are divided into the two types, marker-less application (Figure 1-a) and marker-based application (Figure 1-a). The virtual game overlaps a real scene in the Sky Siege without markers but the AR Defender needs markers in order to draw the same context. The marker-less and marker-based types seem to be very simple but utilize real seamless environments for the background of the games, thus allowing new user experiences in their usual environments such as homes and offices.



Figure 1. Mobile AR projects.

Location-based applications depend on the location-aware technologies such as GPS and WPS in order to overcome the limitation of time and place for providing a variety of contents. The Wikitude world browser, introduced in 2008, projects the local information and landmarks onto the camera's screen. In addition, the Wikitude Drive provides the AR navigation based on the wiki structure. In Korea, the Location-based service (LBS) has become popular. The iNeedCoffee (Figure 1-c) informs us of the location of our favourite brand coffee shops and instruct us on how to go the nearest coffee shop. Espe-

cially, as a platform for AR, the Architecture Walk provides the content of the tourism with the augmented acoustic feature. These applications adopt various spatial and historic contexts which were considered importantly in mobile computing.

SNS applications consider multi-users and more relationships based on the LBS. The Ovjet (Figure 1-d) provides the AR contents with a focus on the relationships among users, objects, and places. It can actualize the personalization of contents, interactivity, sharing, and collaboration.

4. Context immersion in the MR environments

4.1. THE CHARACTERISTICS OF THE CONTEXT IMMERSION

This paper suggests the context immersion to understand new phenomena of having a small display but allowing relatively strong immersion in smart phones. Since smart phones produce the active relationships among the real persons, objects and locations through the social interaction, they could arouse much powerful immersive context which connects users to the real life, not limit them to the imagery world. Rather than adopting confined displays, smart phone can utilize the strength of mobile and ubiquitous computing, thus ambient media can be opened and activated within the boundary of the smart phones.

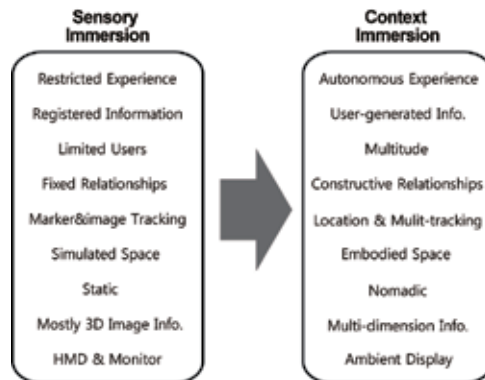


Figure 2. The characteristics of the context immersion.

To sum up, the immersion cannot be fully achieved by the technologies or devices. The important factors that affect the users' immersion are the relationships based on the person, objects and locations in real context. Through the literature review and investigation, we identified the characteristics of the context immersion as shown in Figure 2. The mobile AR applications that

provide LBS or SNS interact on the experience and user-generated information made by multitude. Then, the context immersion generates constructive relationships using location and object tracking. To express various contexts, it uses 3D images as well as texts, 2D images, and other multimedia formats. Also, the context immersion starts at the ubiquitous computing with mobile devices.

4.2. THE CONTEXT IMMERSION IN THE MR ENVIRONMENTS

Compared to the immersion generated by the visual, acoustic, haptics, and motion characteristics (Carrozzino and Bergamasco, 2010), we propose three dimensions of the context immersion in MR environments as shown in Figure 3. The Time and location-based context immersion would be on the increase in the range of static to nomadic for coping with mobility. The Object-based context immersion basically depends on a hard object tracking but utilizes a sophisticate location-aware technology further, thus realizing the object relationships. The user-based context immersion leads to unlimited communications with users networking all of contexts. This type of context immersion evokes user's personalization, interactivity, sharing, collaboration, user making contents, and artistic contents. The immersion expands the SNS (social network services) as a blogging platform using all of contexts such as time, locations, objects, and users.

These dimensions should be applied to smart phone applications for developing an immersive MR, which might provide many possibilities in architecture and design domains. Compared to the traditional CAVE-type immersion, these context immersions could act more effectively to obtain and use physical information on construction management automatically and nomadically (Lee et al, 2009) rather than to visualize and design virtual objects on a table-top (Dunston and Wang, 2005).

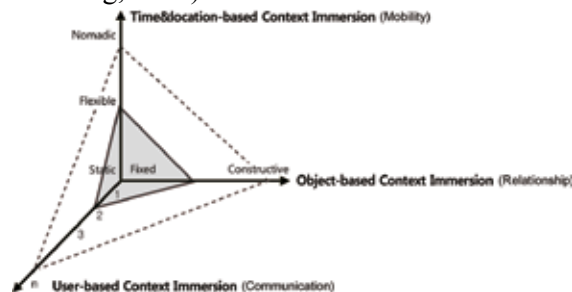


Figure 3. Dimensions of the context immersion in the MR environments.

The time and location-based context immersion pursues mobile relations

using location-based tracking such as GPS and WPS. The immersion would be derived from the degrees of how to overcome constraint of time and space, and what to interact with the context of time and location. The context immersion would promote the MR by taking advantage of unlimited spaces, mobile access, multi-dimensional information, and various displays. Figure 4 shows the mobility of time and location-based context immersion. As seen in LBSs such as the Architecture Walk (Figure 1-c) and the Wikitude world browser, this context immersion has been used to provide the historic building simulation and history as well as the site information using GIS in various applications. This immersion should be considered basically for collaboration in ubiquity beyond the mobility.

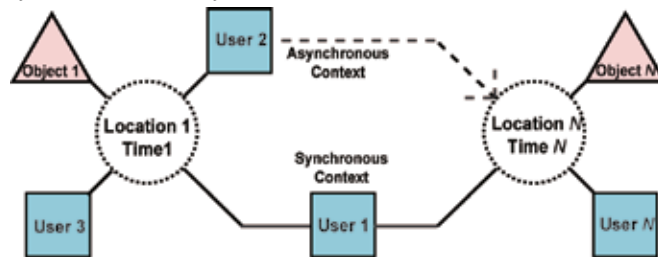


Figure 4. Mobility of time and location-based context immersion.

The object-based context immersion seeks to make the various relationships among objects and to combine a virtual image and a real image by tracking the target object's coordinates based on the marker. This immersion uses a new object recognition and information technology in the ubiquitous computing environments. Especially, our architectural design domain that deals with space can obtain many benefits in the range of loosely coupled objects (Myungho and Kim, 2009) to carefully managed construction objects.

The User-based context immersion could involve various types of user such as normal users, power users, content providers, developers, and service providers (Belimpasakis et al, 2010). Since the users have the goal of communication, MR is a platform as opened Application Programming Interface (API) for the communication. Therefore, power users generate and share their content. As shown in Figure 3, the number of users can be ranged from one user to multiple users. The important aspect of user-based context in the MR environments is how many users communicate with each other. It could be a more immersive environment with many users than one user in MR since we would like to interact and share our experiences with the others. A smart phone has a small-sized display, but affords the context immersion. Therefore, they provide more potentials and challenges for the built environment than the AR in architecture and design (Wang, 2009) since the context

immersion is based on mobility, relationships, and communication. When the mobile applications for architecture and design are developed, these dimensions should be considered to optimize the applications and improve the functions.

5. Discussion and Conclusion

This research introduced the concept of context immersion as a novel approach to the embodiment of MR in ubiquitous and mobile computing based on the results of the literature studies and investigation. To cope with the limitation of location and time in the conventional devices, the mobility and networking of the smart phones are considered for achieving more immersive MR environments that build the interactive relations among persons, objects and locations. Based on the characteristics of the context immersion, three dimensions of the context immersion were presented. The time and location-based context immersion strives for mobility using location-based tracking such as GPS and WPS, enabling unlimited spaces, mobile access and multi-dimensional information. The object-based context immersion is related to the object recognition, making the various relationships among objects. The user-based context immersion allows unlimited communication with users on the network, evoking user's personalization, interactivity, sharing, collaboration, user making contents. The results of this research reveal that the context immersion in mobile MR is different from the sensory immersion in VE achieved by the conventional technologies such as visual and acoustic features. Through the context immersion implemented by mobile and ubiquitous computing, users can be connected to the real life. The understanding of a context immersion of MR can lay the ground for evolving knowledge on the development of immersive MR environments to affect the users' experiences and relationships in real context. This research needs to be thoroughly examined in an experimental study in order to prove the arguments practically for the future by focusing on the MR contents.

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THREE-DIMENSIONAL COMPUTATIONAL STRUCTURES AND THE REAL WORLD

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Abstract. In this paper, we describe a system of composite images to design virtual three-dimensional structures in an outdoor environment. The system, called AmbiViewer, consists of a modeler for three-dimensional on-site sketching, and overlapping locative technologies to orient virtual objects in a real-space, real-time setting. The system employs both GPS orientation and a visual marker system to provide a realistic and interactive augmented reality interface. While it is still under development, the authors believe it can bridge the gap between sketching on site, and creating virtual models in the office.

Keywords. Augmented reality; mixed reality, locative design; interactive mModeler; visualisation; GPS; cybrids.

1. Introduction

Recent developments in digital technology suggest that computation may lead to new forms of virtual modelling (Tonn, Petzold and Donath, ASCAAD 2009). The combination of Augmented Reality (AR) and virtual modeling on mobile devices introduces a wealth of yet unknown and potentially powerful design technologies.

The introduction of cellular smart-phones, tablet computers and camera-bearing music players gives some indication of how the capabilities – and challenges – of AR may affect the design process. Applications like ‘Urban Augmented Reality’ of the ‘Netherlands Architecture Institute’ likewise point in the same direction (www.nai.nl/uar). While the employment of AR is of a practical nature and its development is focused on practical goals, the authors propose that interaction with the spatial aspects of the environment while being a part of it can broaden and enhance creative processes.

In short, developing an architectural design with appropriate technologies while staying on-site is an improvement over gathering data on location and later designing a building with computers in the office.

2. Architectural models

Traditionally the use of architectural models has long been limited to down-scaled physical models. One-to-one scaled projects are not part of the repertoire of an architectural office. With the exception of very few but prominent projects – such as the 1993/94 Berlin Palace simulation with painted canvasses on scaffolds – on-site models are not an option. Their expense is substantial, and their effectiveness in examining alternative is slim at best. In fact, the project in Berlin is likely to have been more a fundraising and lobbying project than an architectural effort. Prior to physical fabrication, a building and its site are only linked during the design process (Abbo 1996). Their abstract union is limited to its presentation, usually at the client's or architect's office. The introduction of computed realities with CAD led to assumptions that such unity could be achieved in cyberspace. In fact such aesthetic integration is impaired by distracting technical interfaces. Because the virtual models depend on technology for their presentation, it is vital that this technology be as unencumbered and transparent as possible.

3. Early designs

Among design technologists there has been a longstanding discussion how to sketch early designs preparatory to their development into complex building schemes (Drexler 1977). With the introductions of CAD systems that question has evolved to tasks of importing early designs into the data model of a specific CAD-system (Clayton and Weisenthal 1991, Gross 1994). Based on the assumption that CAD-design is a secondary step after napkin sketches, the discussion hinges on technical issues of digital measurement, scanning, and other forms of digitization. Then, back at the office, CAD provides the means to create sophisticated, detailed models of the proposed building (Guéna and Untersteller 2008).

This gap separating on-site inspiration from off-site articulation begs the question: How can a building design employ modern computation while being on-site? Whether this can be accomplished is a foregone conclusion – every cell-phone now has more computational power than a workstation of 20 years ago. Instead a better question might be: What kind of digital design do we want? While there may be many answers to this question, our team prioritized design technology that lets an architect to be on-site while designing a new

project, while the inspiration is still fresh.

4. Concepts of AR

For this to happen to the designer must be able to mix virtual architectural objects into real-world images directly on the building site, a technique achieved with present day augmented reality (AR) systems. Such systems' basic concept is to overlay images taken from the real world – digital photos or video streams, with computer-generated objects. These are commonly text messages with some graphical enhancements like images or meaningful icons (Visser 2010) Synchronization the virtual computer view with that of a camera in the real world is emblematic of nearly all Augmented or Mixed-Reality systems.

4.1. REAL-TIME

Producing composite images frame by frame as fast as the video-camera can deliver is another task demanded of AR-systems. While real-time computation is not a mandatory requirement, it is greatly desired and even expected by the user. For this reason alternatives to real-time augmentation were not considered for our project. Instead, accurate tracking of sensors and real-time computation conduce to the intuitive nature of such systems. The resulting computational augmentation feels almost natural.

4.2. MOBILITY

Another important aspect we sought is mobility. The quality of the outdoor AR experience is highly dependent on portability, for designers even more so than players of computer games. This has not been easy to achieve. Our first prototype did fit into a backpack, but impediments cropped up, like the cumbersome deployment of our system, limits of batteries and power cords, or even daylight.

4.3. PRINCIPLES OF AR-SYSTEMS

Common AR-system are divided into tracking-based and marker-based systems. (Avery et al 2008) While tracking-based system are relatively self-sufficient – sensors and processors being integrated within one device – their quality is often wanting. Synchronizing the views of both actual and virtual cameras is crucial, and there is no mediating reference within the image itself. Also the overlay image is sometimes jagged with respect to the actual camera image. Marker-based AR-systems, on the other hand, are known for their quality images. However they are bound to specific locations by the several

markers needed to calibrate the image capturing device. Both AR systems are not really ideal for a real outdoor AR-experience. (Schall et al 2009).

5. Project

Common AR-system are divided into tracking-based and marker-based systems. (Avery et al 2008) While tracking-based system are relatively self-sufficient – sensors and processors being integrated within one device – their quality is often wanting. Synchronizing the views of both actual and virtual cameras is crucial, and there is no mediating reference within the image itself. Also the overlay image is sometimes jagged with respect to the actual camera image. Marker-based AR-systems, on the other hand, are known for their quality images. However they are bound to specific locations by the several markers needed to calibrate the image capturing device. Both AR systems are not really ideal for a real outdoor AR-experience. (Schall et al 2009).

Our project was developed with the goal of designing a system for digitally sketching a building on-site. With the availability of accurate GPS signals, the ability to get accurate measurements, and the increased capacities of portable computers, we created a prototype system, AmbiViewer. This demonstrated the functionality of the idea while revealing several technical shortcomings, common and characteristic problems of developing AR-systems. In the course of integrating two very different aspects of AR we tested almost a dozen GPS receivers, and found that developing the needed software stretched our mental and financial resources to new limits. Waiting time to provide better hardware seemed to be an appealing option.

5.1. LIMITATIONS

AR-systems are commonly based on generating virtual objects as a visual layer over a video image within a display. (Kieferle et al 2003) This priority of augmenting visual impressions neglects the influence of other sensory impressions. They ignore acoustical, olfactory, haptic and other senses, and constrain their access by the designer. If a virtual object can be designed on the site where it is proposed to be, its designer will always be aware of the object's physical and sensory environment.

5.2. SYSTEM

We introduced an approach for a high-quality blending of virtual architectural objects with real-world images directly on the building site. This is done by employing components of either systems of AR: tracking devices and markers suitable for a real outdoor environment; deployable equipment; markers at a

large scale adapted to the scale of buildings; and cameras with possible flexible length. By utilizing an image capturing device, some location devices and a computer the viewing field of the real-world camera is calculated and transposed as view of the virtual camera, which shows the fictional elements rendered according to the values of the input camera.

5.3. HISTORICAL ABSTRACT

A first basic prototype was created and evaluated between 1994 and 1997. After the availability of unaltered global positions the next prototype, the AmbiViewer-system, was developed with a focus on usability and deployability. It utilized a laptop-computer, external cameras, GPS-receivers and a single marker as fiduciary feature. It was in use until the introduction of the iPhone ushered in a new era in AR. An immediate prototype showed the potential, but also some downsides of the new devices. Hence, with the introduction of tablet-PCs the development has moved to a complete new system on mobile devices with large scale markers for super-modelling. It is not yet ready for presentation.

5.4. GEO-POSITIONED MODEL

One significant requirement was the determination of the model's position in relation to the camera. Although it would be easy to define a unique coordinate space like any CAD-system does the decision was very soon to tag every model with its geographical coordinates. At first hand establishing a whole three-dimensional model in GPS-coordinates seemed to be the practical implementation. If every point of a model is defined in global coordinates every virtual shape is logically located on the Earth's surface. A closer look revealed some essential shortcomings. With all data represented in an ellipsoid coordinate system all measured distance were calculated using complex algorithm, and modification by hand, e.g. moving two walls by maintaining their distance, were impossible without the underlying calculations. Even though one example of this approach had emerged, the 'Keyhole Markup Language' (KML) used by the family of 'Google's Earth' application to locate virtual models on digital maps or satellite images is absolutely based on global coordinates, those difficulties led to the approach of simply tagging the models. Therefore the representation of all of three-dimensional models in GPS-coordinates was dismissed. Maintaining an added exact orthogonal coordinate system for measurements only seemed too cumbersome. Instead the model is still based on a regular local orthogonal coordinate system with global positions at hand, but only as reference. All virtual models are tagged

with global positions. Solely the real world objects like marker and image capturing device are connected to GPS-receivers.

5.5. RENDERINGS

With the introduction of OpenGL on mobile phones, especially the iPhone almost all computer related hardware issues were moved aside. Rendering shapes, applying some lighting and textures is no problem, nor is it the composition of the final images. In fact, more serious problems are introduced through the use of higher APIs like whether to use layers or not. These higher APIs very soon might cause performance issues, and in some cases, conflicts. The phone-API in the iPhone, which has always a superior status, simply blocks on incoming calls, and thus the rendering pipe is stalled.

5.6. USER INTERFACE

Complete with camera and GPS mobile devices are now designed to fit in a pocket. Portability is no longer a problem. In addition fully touch-sensitive display offer new methods of interaction. Most important, the new generation of processor deliver the necessary computational power. The example shown here is still quite simple: a location-aware, or locative device captures images with known position and perspective values. On top of the video are some drawings, which then are interpreted and transferred into a three-dimensional shape according to the position and view of the camera, in this special case a ball at the location in fig. 1 labelled with the red pin.

The main UI is based on common and well known mapping technologies as e.g. now 'Google Maps'. From a today's point of view there are no really other option to substitute the layout and the information a map can provide by any other means, especially while noted that there are no fixed scale maps. Zooming, sizing and panning are actions many users are accommodated to.

The modeler is different. It uses the new input methods of smart phones: touches, shakes and other gestures. These new input methods are still unconventional, but they have already proven to be intuitive. It is very easy to draw a shape and put it in place once the technology is available. Acoustic forms of input as e.g. voice commands or more basic whistling and clapping as well as haptic forms like shaking are options.

The implementation of the full range of these methods of interaction is an important aspect of our research. However, as modelling is a common task in digital design and the development of applications with new types of interfaces is ongoing, we recognize that all developers of software in computational design will face similar problems. Besides its demanding necessity, an

iPhone has neither mouse nor keyboard and no emphasis is put on the development of new types of interfaces in the realm of CAD and mobile devices.

5.7. INTERACTIVE MODELER

While mixing views from different kind of cameras is sufficient for tasks like overlaid information or realistic animations the use of it as design tool requires something to create and manipulate virtual objects, because the three-dimensional objects are not simply rendered of ready-made designs. Therefore the Interactive Modeler was introduced. It transfers the AR-system into a design tool. From the beginning our system offered some means to create simple geometrical shapes like spheres or boxes, which then could be grouped, moved, sized or rotated; and coloured or textured. Once the system was hooked up sufficient complex shapes were rendered. On mobile devices now shapes are created with gestures on the touch screen. The virtual model always appears as realistic building in the image. Every modification is immediately displayed as augmentation.

5.8. RESULTS AS DESIGN TOOL

In two cases, each limited and experimental, it was even used as a real design tool. In one project, a design for a play house, an AmbiViewer prototype was used to design the building on site. No working drawings were needed its eventual construction. In the second project, an office space for Caltech Industries, our system was used to demonstrate the space layout to its future occupants. Visitors could walk through the actual spaces, marked with coloured tape on the floors. On the screen, however, they could see each other with the future partitions in place. Because both views, the real world image and the virtual view onto the digital model were synchronized, a composite image was produced, which was sufficient enough to offer the client some choices to work from.

6. Conclusion

In conclusion, our project demonstrates how to augment the world with virtual three-dimensional objects by composing architectural structures and real views in an outdoor environment, and how to manipulate these structures and work with them as architects. During our experiments we located a virtual three-dimensional sphere at a specific location on our site. The sphere was rendered in real time as a computational drawing and then composed onto images of the real world scene. Thus the user could simply perceive size and distance by walking around with his mobile phone. The environment was embodied in the

simulation, not merely a separate mental representation.

6.1. FUTURE WORK

The current prototype is the first implementation of our system on mobile devices. Recent developments demonstrate that new technologies in computation result in novel forms of virtual modelling. The combination of AR's composite images with our interactive modelling on a mobile device gives a sense of the system's potential and capabilities.

The new version on a mobile platform with interactive modeller and locative technologies shows some possible future directions for augmenting the design process. Most mobile devices, smart phones, or tablet computers are very flexible and computationally up to the task. Therefore we should no longer assume that CAD is a secondary step after initial sketches, even if progress is difficult. Combined with new technologies like Augmented Reality and Locative Design the new hardware might trigger a change in the design process. This opens up new forms of the appreciation of unbuilt architecture. Although the objects itself are not real, the distance between them and an observer carrying the mobile device is. The same is valid for the dimensions of the virtual structures.

6.2. DISCUSSION

While our system and its development are focussed on practical goals, it has become evident that the ability to react to the spatial aspects of the environment should not be limited to the visual imagery. We have found that our tool can offer new methods of design based on senses other than the visual.

Techniques combining mobile devices with accurate sensors and capable modelling and designing software blur the boundaries separating virtual objects from the real environment. We believe that virtual architecture need no longer be synonymous with unbuilt. Tools like the Interactive Modeler already point to future methods of design while being on site. At the very least interactive modelling will enhance architects' design capabilities in the early phases. Architectural simulation can have its own validity within our physical environment, and may find uses beyond projecting future construction.

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REAL TIME MODELLING

A solution for accurate, updatable and real-time 3D modelling of as-built architecture

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Abstract. This paper describes a means for 3D modelling that sources photogrammetry data from publically available databases and integrates this data with a real time computer game application to construct point clouds. As the databases receive more data or as the data is updated the 3D visualisation within the computer game environment is capable of remodelling itself to reflect the changes, providing accurate representations of as-built infrastructure within an immersive 3D environment that can be interrogated and analysed in real time.

Keywords. Real-time; photogrammetry; computer game; visualisation; point cloud.

1. Introduction

The range of end users and the resultant need for 3D visualisation applications that suit their requirements has resulted in a fragmentation of 3D modelling and visualisation processes. Many applications exist, some very specific to an end use, and none being a total visualisation solution (if desirable). For the visualisation of as-built architecture, this often results in the need to employ multiple applications to achieve the desired outcome, resulting in complex and tedious workflows and repetition across applications.

Of the various methods to acquire 3D models of existing architecture, the most widely used are CAD tools with 2d architectural plans. Data comprehension remains the longest step in the process with Chevrier identifying 2d

plans as the quickest route to understanding the building scheme. (Chevrier and Perrin, 2009) Common issues that run through each modelling tool are the time required to capture or collect accurate and up to date data, the need for manual input to convert this data into 3D models for visualisation and the maintenance of the data to reflect any changes to remain an accurate representation.

The point cloud, a 3D record of points measured from real environments, has emerged as a flexible method for collection and representation of data, with improved potential for updatability due to the relatively fast and automatic capture of data. The combination of high accuracy and abstract representation allows for the flexibility needed at an early design stage whilst maintaining real attributes and the ability to overlay or intersect multiple point clouds enables comparisons between large amounts of 3D data.

Point clouds can be constructed either from laser scanners, light detection and ranging (LiDAR) sensors or photogrammetry input. Photogrammetry has time advantages, brought about by increased community sharing of images and the ability to combine these to form the data set with less set up time (Fumarola and Poelman, 2009). Progress is being made in the modelling of tourist attractions and large city models in applications such as Photosynth which can be accessed here <http://photosynth.net/> for public creation of smaller data sets, using personal photos or sourced from the internet. As with other 3D viewing applications, Photosynth suffers from the difficulties of navigating and comprehending large amounts of 3D data.

Computer game technology provides a solution to these difficulties in navigating a virtual model with examples presented in the next section. The main advantage computer game technology has over alternative visualising techniques is the ability for the user to be immersed within the environment and the freedom of movement typical of human interaction within architectural space. While there have been recent developments within CAD applications to this end they are still underdeveloped in comparison with gaming engines. In particular, the presentation of information in real time, that can be experienced by multiple users simultaneously.

Section two of the paper provides an overview of existing research into the use of computer games for visualisation compared to CAD and GIS based 3D visualisation. Current developments of point clouds are discussed and automated modelling from others research is analysed. The literature review identifies gaps within the research that, along with recent advancements within computer gaming engines to provide a new modelling solution, develops the aim of the paper, presented in section three.

The method for this new modelling solution is presented in section four

with the introduction of a case study. The results of this case study are presented in section five while section six is an analysis of these results and a discussion on limitations and areas of future development or new applications before the paper concludes in section seven.

2. Background/literature review

Previously identified limitations of CAD and GIS applications for the visualisation of 3D models include difficulties for the average user in seeing space intuitively and in a manner that is easily understood (Germachis et al, 2005). CAD and GIS initially focused on the 2D view and to a large extent still do, as the 2D view is a common output for work on site. As a result the pan, zoom and rotate tools of 2D documentation have been extended within these applications to provide navigation in 3D as well. Pelosi (2010) acknowledges that while the construction of a 3D model may benefit from these tools, the viewing of a 3D model using these tools can be frustrating. This is not helped by the use of the mouse as the primary method to navigate which Pelosi (2010) identifies as ‘a complicated and confusing navigation method to learn and control.’

The popularity of computer games and familiarity of navigation techniques across many users is seen as an advantage over CAD and BIM systems (Pelosi, 2010; Germachis et al, 2005). However, the intuitiveness of using a keyboard and mouse for navigation within these computer game engines has been questioned (Laing et al, 2007). As with any computer application, computer gaming engines require some getting used to for new users. Should computer game use continue to rise and be more evenly represented throughout the community, as appears to be the trend (Brand-J, 2007), the issue of intuitive navigation for users of computer game engines will decrease. The development of gaming platforms, such as Nintendo Wii and Xbox Kinect, further reduce this issue as navigation is more intuitively linked to user movements. BIM and GIS applications, due to their relatively high costs and specialised use, are unlikely to become more accessible to casual users without a change in their navigation system which is familiar to a wider audience. Such changes have been recently developed for some CAD and GIS applications allowing a first person type walkthrough ability, suggesting that the developers of such applications recognise the benefits that computer game engines have in this area.

There are numerous processes for translating CAD models to computer game engines for improved visualisation capabilities. (Indraprastha and Shinozaki, 2008; Friese et al, 2008; Laing et al, 2007) The time required in all processes is not insignificant and the ability to update changes is limited. Updatability is limited by the need for on-site images to provide texture infor-

mation and changes in geometry often require editing to the 3D model within the original application before re-exporting to the computer game engine.

Point clouds reduce the need for manual input and can quickly produce detailed 3D models (Shih and Wu, 2005; Fumarola and Poelman, 2009). Nir and Capeluto (2005) identify a growing use of point clouds in architectural design in the later stages of the design or fabrication process. This can be seen in Shih and Wu (2005) where the point cloud is used as a means of measuring as-built progress on a building site. Point clouds are taken once a week and compared by way of intersection to determine the areas of progress. Nir and Capeluto (2005) demonstrate the use of point clouds used for early conceptual design development.

Despite the advantages point clouds have of relatively quick capture and creation of 3D models when compared to CAD and GIS applications they share the difficulty that data is hard to navigate. Perhaps more so; as more data is captured, more points are produced and the difficulty to clearly see the points of interest increases (Chevrier and Perrin, 2009)

3. Aim

The aim of this paper is to present a solution that will provide an end user with access to large, accurate and flexible data within an environment that allows navigation and visualisation amongst multiple simultaneous users. Using computer game engines will enable the data to be more easily interrogated and navigated and challenges the idea that point cloud datasets are not able to be viewed directly within a virtual environment due to their size (Fumarola and Poelman, 2009).

4. Method

The process follows well established data capture and conversion techniques. LiDAR and photogrammetry both yield suitable point cloud data. In the interests of updatability and time saving, photogrammetry shows the most promise. Current community databases contain large amounts of accessible and searchable images and are updated by the community removing the need for manual data collection on the part of the developer.

Photosynth provides the platform for grouping these images together and creates a point cloud as a function of the relationship it creates between the images. Bundler is the basis of Photosynth and if used on its own can create higher detail point clouds but doesn't have the database that Photosynth has of community made point clouds. Using bundler would allow higher resolution images to be used for image matching and hence increase the detail of

a point cloud. However, this would limit the automation of the workflow as point clouds would always need to be created, whereas Photosynth has an existing library of point clouds already converted from the raw images. It is quite likely, as this database grows, locations that a user may be looking to document have already been uploaded to Photosynth, and as these locations change, users may produce newer point clouds that reflect these changes.

Point clouds are exported from Photosynth using an open source exporter, SynthExporter, available at <http://synthexport.codeplex.com>. The exported file created is a *.ply file and is readable and editable in any text application. Data captured from LiDAR would remove this step as the point cloud would have already been captured. However, additional steps through 3D modelling applications would be required to achieve a suitable file format to link with the computer game environment.

The computer gaming engine used is the CryEngine2 gaming engine developed by Crytek and used to develop the Crysis series of first person shooters. Previous research (Friese et al, 2008) identifies advantages that CryEngine2 has over alternatives, namely CryEngine's editing tools.

The link between the point cloud data and the computer game environment is achieved through the application of a Flowgraph Plugin System (FGPS) developed by a member of the Crysis community, James Ryan (www.crymod.com) for CryEngine2. The FGPS allows the Sandbox2 to interrogate *.xml files so that they may influence a variety of game play elements in real time. The *.ply files are converted to *.xml in a format that represents each vertex and associated colour information in consecutive nodes. The FGPS reads through each node and responds to any changes as they occur. These changes are then viewed and interacted with as the user moves around within an immersive 3D environment. Users are able to view the data from any perspective but also influence the data itself.

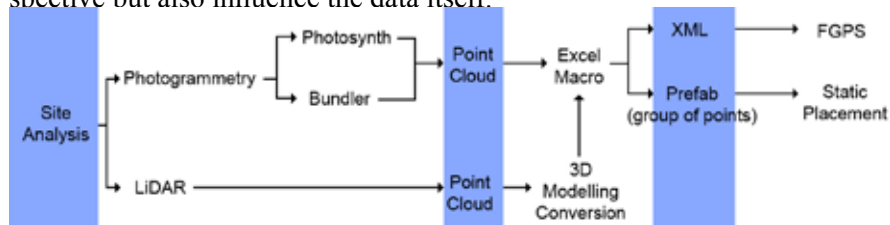


Figure 1. Diagram of method.

The workflow in Figure 1 is demonstrated in an Australian Research Council funded project (ARC LP 0991589) that is contributing to our understanding of urban space in a major Australian city. The project involves crowd model-

ling and analysis utilising sensor driven avatars within a computer game environment (CAADRIA 2011, Lowe, Hedley and Goodwin). In the case of this crowd modelling and analysis an abstract point cloud model was not a desired end result, rather a typical 3D model was required for user recognition for visualisation and simulation exercises.

5. Results

A number of point clouds were successfully created within the gaming environment, having been sourced from various point cloud creation techniques. Initially small sample sizes of point clouds that were manually created within a text application were brought into the game environment to test the workflow and the computer games ability to manage the data. Ply files were then exported from various existing Photosynth files available in the community. An example is shown in Figure 2. These point clouds require some editing to get them into an *.xml format that the FGPS can read. This is done using an Excel spreadsheet and a macro script created for this purpose. This proved the

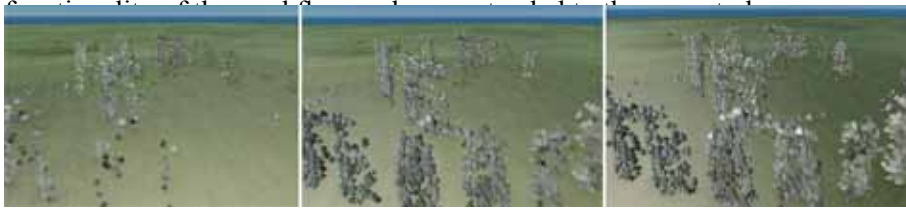


Figure 2. Stonehenge Photosynth as point cloud within gaming engine showing increasing detail – 1500, 3000, 4500 points.

5.1. CASE STUDY

To produce a 3D model that was recognisable for simulation exercises was problematic due to the buildings age, lack of historical importance and consequent lack of accurate architectural drawings as well as the fragmentation of these drawings. In this case study the point cloud creation and integration within the computer game provided a technique for checking the accuracy of the model constructed from drawings. The point cloud was constructed using Photosynth and images extracted from video footage taken during site visits.

This represents a likely process in the case of specific projects where data is not readily available and community image databases do not have the necessary amount of information. This could occur in areas that are not popular tourist destinations or where photography is limited for security or other

reasons. The decision to capture site information using a video camera made data collection less intrusive in an area continuously being used by the public. Video footage also ensured there was adequate coverage of the area, whereas capturing static photos was more likely to have missed areas of interest and possibly requiring more time consuming site visits.

The point cloud data was then compared to the 3D constructed model to check the 3D constructed models accuracy. Such a use for point clouds has been used extensively in previous studies and applications (Shih and Wu, 2005; Fumarola and Poelman, 2009). The added advantage that this process has, is the ability to combine the two models within the computer game environment. This allows multiple users to analyse the two models from any perspective, independent of each other. It produces a virtual site visit in which discussions can occur within a group as each member interrogates the model. Figure 3 shows views typical of what a user would encounter within the game environment.

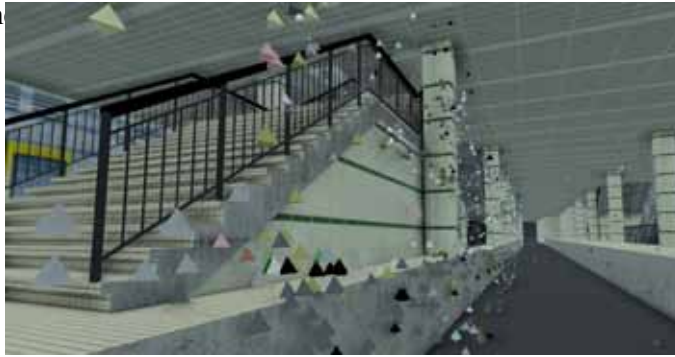


Figure 3. Conventional 3D model with overlaid point cloud within gaming engine.

This process, from Photosynth to CryEngine maintains colour information from the *.ply file and allows each individual point to be created within the gaming environment with its correct RGB colour originally captured by the photogrammetry. This removes the need for texture creation or mapping within a 3D modelling program, a process that is required for almost all visualisation applications and one that has been regularly identified as requiring a lot of time and manual input (Shih and Wu, 2005; Laing et al, 2007; Fumarola and Poelman, 2009). In addition there is little scope to maintain this texture data in a typical application as any changes will require the modeller to start from the data capture step in order to update the texture information.

It is possible to import the point cloud data into the game in a number of ways. One option was for each point to be created (the FGPS refers to this as

the point being “spawned”) individually, one after the other. The rate at which points are spawned and how many are spawned, or the interval between each being spawned, can be controlled and allows for a flexible form of analysis. Alternatively a group of points can be spawned together to get a more immediate representation of the point cloud but also to break up the point cloud for visual, functional or analytical reasons.

Currently points are spawned based on a default order that is generated in the conversion from Photosynth to the *.ply file. As a result each point is identified based on this order. However the FGPS allows for great flexibility in this area with scope for more specific identifiers for editing and change management. The FGPS also allows for the export of the point cloud information from the gaming environment which provides a robust system to compare and analyse changes.

6. Discussion and further opportunities/applications

The ability to visualise 3D point clouds within an immersive computer game environment has obvious advantages for viewing information and being able to navigate it successfully (Manovich, 2000). Typical mesh and texture mapped 3D models are unlikely to be replaced by this workflow in the short to medium term as they still represent the most accessible, conventional and photo realistic environments to the public (Fumarola and Poelman, 2009).

From the analysis of the case study and the previous trials of manually created point clouds it is evident that the combination of current computer memory allocation and the generation of point clouds as massive collections of simple objects (four polygon tetrahedrons) limits the size of the point cloud representation in Crysis. On the computers used for testing (high powered graphics workstations), point clouds larger than 10,000 flashed and became unstable graphically when imported as a group. Similarly, individual points spawned from a point cloud of around 10,000 suffered some time delay with significant drop in frame rates as the computer game scene became over populated. It is expected that computer speeds and memory limits will improve significantly, thereby improving the scope of these results. There is however a large gap between 10,000 points and the million or so points one regularly see's in point clouds of popular environments.

One branch of our future work in this area involves automatic meshing of point cloud data captured by robotic devices and initial experiments show enormous promise where Crysis represents 250 meshes (instead of 10,000) but with each mesh containing 10,000 polygons, with no noticeable issues.

Another area of exploration being pursued is the ability to create meshes within the game instead of geometry to represent the position of the points. It

is feasible that instead of spawning geometry at the x, y, z locations contained within the *.ply file that a flowgraph could be developed to connect vertices in the point cloud and create polygons creating a 3D mesh in the computer game environment. Conversely, if computer memory and application limitations allowed, point clouds could be made dense enough so as to remove the need for mesh geometry. Ultimately these approaches could replace 3D modelling software in creating photorealistic virtual environments.

Finally, an extension of the workflow is being explored to provide a system for modular and prefab design. As the point cloud data determines where a mesh is spawned within the computer game and the user has control over what meshes are spawned at each point it is possible to create a matrix of positions of regular elements. This matrix can then be edited, just as the unstructured point clouds obtained from photogrammetry can be. A design can then be modelled from a library of parts and edited quickly and accurately. The design of a health care facility is an example of an architectural program that would benefit from this approach as the spatial requirements are quite rigid with rooms and equipment repeated regularly.

There remain some gaps in the automation of the workflow that require manual input. The process of exporting a *.ply from Photosynth and converting it to a suitable *.xml format is an example of one of these gaps. The development of the macro script mentioned above greatly improved this but should be taken further. An application will be created that can continually export Photosynth point clouds and reformat them in a FGPS readable format to keep the content as current as possible, if not in real-time.

7. Conclusion

The workflow presented above can immediately benefit the development of conceptual designs. Environments can be created in which conceptual designs can be experienced, interrogated and edited in real time through the use of the FGPS, while being located in a spatially, geometrically and texturally realistic representation of existing surrounding architecture and landscape. This extends existing applications of point clouds for conceptual design but by including site information earlier can improve the design decisions at an earlier stage (Nir and Capeluto, 2005).

The creation of a 3D model for typical visualisation purposes is time consuming and is often repeated by multiple modellers for the same building. Checking the accuracy of such 3D models against existing environmental conditions can also be as time consuming and as tedious as creating a new 3D model. The point cloud workflow may be an alternative to multiple site visits and can remove the need for site visits all together if community image data-

bases contain suitable information for the project. Coupled with the ability to easily navigate the point cloud within an immersive computer game environment, the workflow demonstrated provides a viable solution to providing reliable 3D models. The accuracy of the point clouds within the 3D environment was validated by a comparison to a 3D model created using accurate architectural and engineering drawings as can be seen in Figure 3. The workflow may also greatly reduce the time and manual input of existing processes whilst adding confidence in the accuracy of any conventionally created models that may still be useful.

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REAL-TIME POROSITY

Combining a computer game engine with environmental sensors to better understand pedestrian movement in public/private space and in real-time

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Abstract. This paper describes the theoretical context, design, implementation and evaluation of a novel method for understanding pedestrian movement in public/private space. It examines the pedestrian counting and tracking methodologies of Space Syntax and proposes an alternative methodology that links sensors embedded in real-world environments and carried by pedestrians with an environment and avatars in a contemporary computer game. In this way observers are able to closely trail pedestrians without affecting their decision making. Results from a field trial are presented where the sensors and computer gaming technology were tested within a challenging real-world environment.

Keywords. Pedestrian movement; public/private; Space Syntax; environmental sensors.

1. Introduction

Artist/Architect Richard Goodwin coined the term Porosity as it relates to the public and private space of the city in 1996 (Goodwin et al, 2006). Goodwin classified a series of private spaces as types of public spaces. These spaces reach from conventionally public spaces (streets, footpaths, plazas) deep into private space via lobbies, atria, elevators, corridors, waiting and restrooms. He notes that if a visitor is able to spend 15 minutes in the restroom on the 14th floor of a building (on their way to an appointment with their accountant for

example) then the restroom should be considered a 15 minute public space.

With support from the Australian Research Council Goodwin conducted a major study from 2003-5 which created a snapshot of the Porosity of three major buildings in Sydney, Australia (Goodwin et al, 2006). In that project he extended the work of Space Syntax (Space Syntax Limited, 2008) by recognising that not all spaces are equivalent in terms of public access. In many cases this would reshape the graphs of Space Syntax by altering the number and topological relationships of the spaces under consideration (reconsider, for example, the Space Syntax map of London and their analysis of the Tate Modern art gallery (Vaughan, 2007). The three dimensional effects of this delimiting of space by public access can be seen in Goodwin's 'Cactus Models' (Goodwin, 2007).

In contrast to Space Syntax, at the core of Porosity is its transformation over time; implicated by the constant testing and renegotiation of public and private space through human use and aspiration. Ultimately then, we need to extend the single snapshot of the Porosity of the city to a sequence of snapshots so that we can better understand the way people move through it over time. But as opposed to animation, where there is a predetermined narrative, these snapshots should be able to be interrogated from many different points of view, in real-time. To be useful for understanding dynamic situations they should also be recorded and represented in real-time.

The challenge of understanding the movement of people through space is a particularly compelling one; not least because of the complexities involved and the growing list of applications such an understanding could support (Sangwan, Qiu, and Jessen, 2005; Behzadan et al, 2008; Foxlin, 2005; Krumm et al, 2000; Yan and Forsyth, 2005; Hightower and Borriello, 2001; Rolland, Davis, and Baillot, 2000). The particular application motivating this research is to develop a better understanding of pedestrian movement through a major urban subway station so that the relevant agencies are better able to make decisions relating to the design of urban infrastructure.

The strength of Space Syntax could be inferred by the sheer number of research projects that have applied its methodologies in dozens of cities and buildings around the world. Time and time again studies have shown a correlation between Space Syntax's metrics and pedestrian movement observed on the ground. But for the authors gaps begin to appear when one looks closely at the observational methodology employed by these studies. Space Syntax methods come in three forms; gatecounts, static snapshots and trails. Recently Kostakos (2010) described all three methods but while these descriptions answer many questions several key areas remain vague. Over the years a great deal of criticism has been levelled at the theories of Space Syntax (Ratti, 2004).

Somewhat surprisingly Ratti's thorough account does not mention pedestrian measurement methodologies or the accuracy of Space Syntax pedestrian counts. The authors argue that each method is pragmatically flawed in some way and that by extension any correlation to data gathered is equally suspect.

However, the authors suggest that the trailing methodology is the most robust of the three but that it too suffers from a lack of scalability. The desire to link individual level mechanisms with population level observation has promoted a drive towards pedestrian simulation by researchers in this area (Penn and Turner, 2001; Batty, Jiang, and Thurstain-Goodwin, 1998; Ratti, 2004). Pedestrian simulation may overcome the limit of scale but sacrifices the depth of information gathered and seems counter to the noted strength of Space Syntax; it aims to explain how cities *are* rather than how they should be (Kostakos, 2010).

On the surface it would seem that to trail more pedestrians one simply requires more observers. While it's clear that to have 500 observers following 500 pedestrians is not only impractical it would skew the behaviour patterns that arise from mechanisms such as flocking. The question becomes; how might one be present in a space alongside the pedestrian being trailed without actually being there and affecting the results?

In response to this question the authors have designed a system that captures the location of multiple pedestrians via Radio Frequency wireless sensors and translates them in real-time into a modified computer game environment that replicates their physical environment. In such an environment observers are able to trail pedestrians, observe them from many different points of view and are even able assume the pedestrians point of view ... all without a bodily presence in the real space, along with the influences that might create. Following preliminary testing within a laboratory environment the system was trialled within a major public space for further evaluation. This paper will describe the design and implementation of the system in detail and report on its current performance. The paper will conclude with notes on future work.

2. Aims of the research

In support of the overall goals of the Real-Time Porosity project, to record, represent and analyse Porosity in real-time (so that this understanding might influence architectural and urban design), the key aim of this experiment was to test an alternative to the trailing methodology developed by Space Syntax. For this experiment the researchers developed a novel link between the computer game engine CryENGINE2 and a Radio Frequency (RF) tracking system developed by the CSIRO. Previous research (Lowe and Goodwin, 2010) tested this linkage in a conventional office environment where the RF

tracking technology was known to perform well.

3. Wireless ad-hoc system for positioning:

As is commonly understood GPS works well when the item to be tracked is visible from the sky but is severely limited in most indoor scenarios. In these circumstances other tracking, or localisation, systems are required. A number of techniques have been attempted and include video (Yan and Forsyth, 2005, Krumm et al, 2000), computer vision, inertial sensors (Foxlin 2005), WLAN (Behzadan et al, 2008), and RFID (Sangwan, Qiu, and Jessen, 2005); however none has been sufficiently successful. Video based techniques suffer from low resolution and perform poorly in crowded environments due to targets being obscured. Inertial techniques fail after a short time interval due to uncorrected sensor drift. Techniques using RFID require significant setup of infrastructure and techniques based on received signal strength have poor accuracy and don't adjust to changes in the environment; which are continual in environments of interest. That leaves as the only possible candidate the class of tracking techniques based on measurement of time of arrival (TOA) of radio signals. Up until now these have generally been rejected due to the difficulty of performing highly accurate measurements of TOA in indoor environments. Indoor environments, particularly in areas such as subway stations, suffer from multipath reflection whereby radio receivers obtain multiple copies of a transmitted signal due to reflections of the transmitted signal from multiple surfaces in the environment. These have varying delay and phase and combine to corrupt the original signal at the receiver.

The CSIRO has developed world leading technology that is able to perform accurate TOA based localisation in challenging radio propagation environments using low-cost hardware. This platform is called WASP (Wireless Ad-hoc System for Positioning) and was developed for applications including tracking athletes for performance monitoring and training, tracking fire fighters in large buildings to enhance their safety and tracking vehicles and people in underground mines for enhanced safety and productivity. Another feature of the WASP platform is that it was developed for rapid deployment in unknown environments. This set of features makes WASP ideally suited to the current application.

A radio localisation system consists of devices (often called tags) attached to the person being tracked, and devices (often called anchors or base stations) positioned at known locations that form the reference for tracking (these are analogous to the satellites in a GPS system). The hardware has been previously described in (Hedley et al, 2007) and the processing algorithms were presented in (Humphrey and Hedley, 2008) and (Hedley, Humphrey, and Ho,

2008). The remainder of this section provides a brief overview of WASP.

Two versions of the WASP hardware have been built, and are shown in Figure 1. Both have the same radio and signal processing electronics, however the larger node (115 x 90 x 55 mm excluding external antenna) has a larger 6.5 Ahr battery for longer life and greater connectivity options, while the small node (90 x 50 x 25 mm) has a 1.9 Ahr battery and a compact internal patch antenna. The radio operates in the 5.8 GHz ISM band with a transmit power of up to 100 mW and the receiver has a noise figure of 5 dB.



Figure 1: WASP node hardware, with tag on left and base station on right.

The accuracy achieved by the WASP depends upon the particular radio environment, however in indoor environments under line of sight conditions median error is usually better than 0.25 m. A custom communication stack was designed to support the particular requirements of accurate tracking and it also provides a data network with data rates up to 8 Mbps so that location data, and potentially other information, can be transported to a computer monitoring and recording the trial, and providing a real time display of tracked locations.

The technical requirement of the trial was to record the location of several research assistants wearing tags while moving about the subway station for subsequent analysis. The WASP setup required the installation of a number of fixed base stations around the station and required the location of these nodes. The location was determined by finding their XYZ coordinates in the previously constructed computer game environment of the station. The anchor nodes were positioned to be inconspicuous in the environment with a distribution supporting accurate tracking. This required that from any location on the

station that there was a line of sight to at least four anchor nodes; satisfying this requirement lead to the installation of 14 base stations.

To enable the real-time display of the location of the targets in the gaming environment a monitoring computer connected to the WASP network was connected via Ethernet to an adjacent high performance computer. This computer was ran the gaming engine that displayed the tag (and hence target) locations.

4. Interfacing with the computer game engine using the Flow Graph Plugin System (FGPS):

Tracking the pedestrian is the first part of an alternative technique required to capture the deep information that a researcher would get by in person trailing. The second part is to translate that data into a form whereby the researcher is able to be co-present with the pedestrian being trailed. The use of contemporary computer gaming technologies for visualising, navigating and interacting with spaces and other users has been well documented and suits these purposes (Lowe and Goodwin, 2009; Sun, De Vries, and Dijkstra, 2007; Conroy Dalton, 2001; Shiratuddin and Thabet, 2002; Germanchis, Pettit, and Cartwright, 2005; Laing et al, 2007; McGrath and Hill, 2004). For this research the authors developed a unique extension of a contemporary computer game by linking AI controlled character movement within the computer game environment with pedestrians carrying RF sensors.

Game editors for Unreal Tournament 3 (UnrealEd by Epic Games) and Crysis Wars (Sandbox2 by Crytek) are provided by the developers and enable the creation of environments (or mods) that may be accurate facsimiles of real-world environments. In addition these two game editors provide a visual scripting mechanism to enable the creation of complex forms of interactivity (in Sandbox2 this is called the Flow Graph). In addition to modifying environments the community of modders for Crysis Wars have modified the Flow Graph within Sandbox2; one particularly significant mod is called the Flow Graph Plugin System (FGPS) (Ryan, 2009). The FGPS provides a mechanism for the game engine to read data from XML formatted files. The authors took advantage of this to link characters controlled by AI within the game environment to XYZ location data of pedestrians provided by RF sensors. To our knowledge this innovation remains unique. The link between the location data in the XML file and the AI controlled characters is as follows; the Flow Graph reads the XML file once per second then repositions a target with the XYZ coordinates it finds there and finally instructs an AI controlled character to head toward the target. Please follow the link below to download the necessary files, and setup instructions, to replicate this part of the experiment: www.russelllowe.com/publications/caadria2011/caadria2011.htm

Following this loop the AI controlled character may not reach the target before the target is repositioned (the WASP system is capable of providing coordinates at 20 Hz and in this field trial was delivering coordinates at 5 Hz) so there is, in effect, some smoothing of the data that is dependent on the 'physical' speed of a character in game. There is currently a one second lag between the pedestrian's position and the position shown by the computer game but this is an arbitrary interval and can be adjusted to provide the best balance between AI smoothing and short lag time.

The pedestrians in the field trial included members of our research team and members of our research partners, no members of the public were tracked in this study. Our pedestrians were tracked either singly or walking in pairs, in single file. The tests were conducted over four non consecutive days in July/August 2010. Three of the tests were outside of peak commuter periods (10am-2pm) with one during the evening rush hour (4pm-8pm). Estimated numbers of pedestrians on the platforms ranged from 100 people, off peak, to approximately 1000 people at peak. The performance of the tracking algorithm was quantitatively evaluated as follows. A person carried the node in a straight line parallel to the edge of the platform with a distance from the edge of approximately one metre. These pathways enabled benchmarking with known geometries.

5. Results, discussion and conclusion

The location of the node was tracked by WASP, and for each computed location the distance from a line one metre from the edge of the platform can be determined. This provides the errors perpendicular to the line, and under the reasonable assumption that the errors are isotropic, the errors parallel to the line have an identical distribution so we can estimate the total tracking error. The median error was 0.38 m, and 90% of the locations had an error of less than 1.05 m. The distribution of errors for this data had a large tail as there are a number of locations in this complex environment from which blockage by building structures prevented line of sight signals to sufficient anchor nodes to obtain a good geometrical dilution of precision (GDOP).

Due to the direct 1:1 relationship between dimensions in the virtual environment and those in the real world environment the XYZ positions of the targets inherit the level of accuracy delivered to them from the WASP monitoring computer. The smoothing effect created by the AI generated pathway serves to reduce error margins when the pedestrian is moving in a straight line, but may result in the avatar cutting corners from the pedestrian's pathway as they turn corners. This departure from the true path is limited by distance a pedestrian travels between each interrogation of the XML data by the com-

puter game engine.

The ad hoc installation of sensors did cause some anxiety amongst the travelling public and could reasonably have been expected to alter their normal navigational patterns. But to achieve sufficient localisation accuracy in cluttered environments it was necessary to build a custom system, however with the development of standards and consumer electronics in the future it will be possible to track the mobile phones carried by most pedestrians. Future WLAN standards, such as 802.11ac already in development, will utilise many times the radio bandwidth of current standards. As mobile phones increasingly provide WLAN connectivity it will be possible to track the pedestrians using the high bandwidth WLAN signals from the mobile phones that they carry and a fixed infrastructure of custom anchor nodes. This will mitigate greatly the impact that carrying such a device would have on the navigational decisions of the pedestrian.

Recently a virtual world platform called Blue Mars (Blue Mars, 2010), which uses a version of the Crysis Wars game engine, advertised an option for over 4000 concurrent players. Future work will investigate this platform as an opportunity for expanding the numbers of pedestrians in the study (as well as the use of mobile devices, such as the iPad, to interrogate the resulting movement patterns). Other opportunities include feeding additional environmental data into the positioning algorithm. This research and the field trials demonstrated an alternative methodology to manual pedestrian counting, static snapshots and trailing. In addition to providing accurate positioning of pedestrians it provides an opportunity to be present in the space without being physically present in the real world environment. Further opportunities exist to extend the work into areas relating to hazardous environments (construction site visits for example) and other sensitive operational environments (such as the emergency departments in health care facilities). With massively multi-player online environments such as Blue Mars utilising cloud computing to deliver compelling virtual worlds to mobile computing devices the future for automated pedestrian analysis using real world sensors and computer gaming technology looks very bright.

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VIRTUAL AND INTERACTIVE ENVIRONMENTS II

23.	Indirect biofed architecture: Strategies to best utilise biofeedback tools and interaction metaphors within digital architectural environments	241
	<i>Erik M. Champion and Andrew Dekker</i>	
24.	Preliminary experiments of OPENSIM performance evaluation for virtual design studios	251
	<i>Walaiporn Nakapan and Ning Gu</i>	
25.	Simulating 3D architecture and urban landscapes in real space	261
	<i>Shun Watanabe</i>	
26.	First steps of the augmented design studio: The interconnected Hybrid Ideation Space and the CI Loop	271
	<i>Tomás Dorta, Yehuda Kalay, Annemarie Lesage and Edgar Pérez</i>	
27.	Interaction in terms of individuality and intelligibility	281
	<i>Hao Hua and Ting-Li Jia</i>	

INDIRECT BIOFED ARCHITECTURE

Strategies to best utilise biofeedback tools and interaction metaphors within digital architectural environments

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Abstract. This paper explains potential benefits of indirect biofeedback used within interactive virtual environments, and reflects on an earlier study that allowed for the dynamic modification of a virtual environment's graphic shaders, music and artificial intelligence (of Non Playing Characters) based on the biofeedback of the player. It then examines both the potential and the issues in applying biofeedback (already effective for games) to digital architectural environments, and suggests potential uses such as personalization, object creation, atmospheric augmentation, filtering, and tracking.

Keywords. Virtual worlds; biofeedback; sensors; empathy theory.

1. Introduction

This paper argues the converse to the 'liquid architecture' theory of digital worlds posted a decade ago by Novak (1991). Rather than a liquid realm, we may wish for vague digital media boundaries that congeal or even solidify on interaction, in order to direct people into different cognitive realms, and afford a wider and richer range of interactive modes and contextual information. Unfortunately, architecture (as a built place) has too often been viewed as an art form that relies on its aesthetic value in terms of being an immovable and immutable object. For example, in the nineteenth and twentieth century,

empathy theorists viewed architecture as little more than sculptural objects that we can create associations for (Mallgrave and Ikonomidou, 1994; Leech, 1979; Newmann, 1995). The philosopher Anthony Savile (1993) attacked Richard Foster's work for the same reason as the empathy theorists: treating the essence of architecture as sculptural form. For Savile, architecture also involves interior spaces, the linking of spaces (e.g., from inner to outer and the converse), and the placing or locating, using and imagining of symbolic objects (as well as the self and other people) in order to create a significant sense of place.

However, virtual worlds and digital architecture in general do seem to be abstracted form. The experiencing of architecture in a virtual environment typically lacks the richly embodied and visceral experience of visiting and moving through real world architecture situated on changing terrain and visited during changes of light, heat, atmosphere, and sound. Technical limitations may be part of the issue, but a further factor is the inability of current virtual environments to adapt meaningfully to the participants. Could biofeedback help address this lack of rich embodiment in digital environments?

2. Definition of biofeedback

We use the term biofeedback to represent a real-time two-way feedback loop between the machine and the user: the user reacts to an action initiated by the system, and the system can then react based on the users physical/emotional reaction (and so forth). Biofeedback interaction does not necessarily form the primary mode of interaction, but augments existing interaction. In the following case study we focus on the use of such devices within gaming environments. While the initial implications are for games (Koutepova et al, 2010) there is also widespread potential for many forms of digital interaction (Fairclough, 2009).

5. Biofeedback in computer games

For First Person Shooter (FPS) computer games, biofeedback can help in the visual and audio adjustments of the avatar and HUD (Heads Up Display). Manipulation of the game environment and events, and enhancement of generalised gameplay can be affected (player speed, strength and avatar abilities). Low galvanic skin response helps with aiming of weapons. High heart rate might assist with agility and movement.

There are also stealth games, which could require the user to remain calm while walking through the city, avoiding suspicion, and monitor their breathing and heart rate when using a weapon to perform, say, an assassination.

They may have to raise their heart rate to move faster during an escape, but also keep their skin response low in order to remain focussed. Similarly, for jail breaking: when speaking with Non Playing Characters, or when hiding objects, the user must remain calm to be inconspicuous. Traditional game interfaces to accomplish these kinds of interaction do not create a breakdown between the user and their avatar.

In the developing world of social player games, biofeedback can also help provide other players with information on the trustworthiness of the player. After all, the lie detector is a simple form of biofeedback. Biofeedback can also be used to trigger automatic facial behaviours or physical gestures in the avatar. Boredom could trigger certain avatar characteristics so that other players realise this player is not fully engaged, but this could also be accomplished with eye tracking, which is part of the CALLAS research project (2010), but not discussed in this paper due to space restrictions.

4. Past work: case study

In the following case study (Dekker and Champion, 2007) we investigated how commercial biofeedback devices could be integrated with existing computer game environment. This study utilised the Wild Divine sensor technology, which includes a device that clips onto the fingers. The Lightstone measures the ECG HRV (Electrocardiogram Heartrate Variability) and the GSR (Galvanic Skin Response) of the user in real-time. While these measurements do not give enough information to make a complete Biometric Analysis (Beckhaus and Kruijff, 2003), they provide insight into participants' reactions to specific game events.



Figure 1: Wild Divine Lightstone biofeedback sensor

The Lightstone device (Figure 1) has the potential to measure: anxiety and stress, relaxation and meditation, tension, sudden changes in mood, and breathing variability. EEG was not used due to ethical considerations.

We developed sockets for the Wild Divine biosensor, enabling us to use them for commercial games and for virtual environments. We conducted tests on fourteen users, and found some interesting results. For our experimental design we modified an existing zombie horror level developed in the Half-life 2 Source game engine by connecting wild divine sensors. Invisible boxes in the game level detected the biofeedback, and depending on the biofeedback registered whether the user was calm or excited, creating changes in apparent time (bullet time effects), music, and visibility (a calmer participant could see through walls or even become invisible to their enemies).

Filters (Figure 2) were also applied to the game if the player's heartbeat was faster or slower than average. If the user's heartbeat and galvanic skin response was over 3 times their average, the screen became bright red, the field of view of the avatar would change to 130 degrees and the speed of the avatar would dramatically increase (to simulate a 'berserker'). A calmer heartbeat turned the display black and white or faded it to white, while an excited heartbeat caused the display to fade to red or further, to shake, to represent a lack of control.

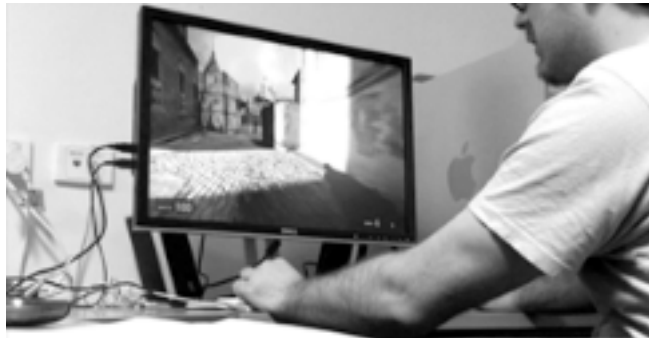


Figure 2. Half Life 2 and Biofed Shaders

To compensate for possible problems associated with this method of analysis, readings were averaged at two-second intervals. The current average of the participants' biometrics were compared against the calibration average, to create a multiplier. The three multipliers (heart rate variability, skin response and heartbeat) dynamically changed the game environment.

Some observations: participants' changes in facial expressions were easily comparable to the change in biometric information (we also used video cameras to track the players and the onscreen action). Audio effects had a considerable effect on participants' biometric information and reactions. The dynamic shaders clearly affected the users. Black and white visualisation calmed users. The red filter visualisation did not affect biometric information

significantly. The white screen visualisation confused users. Users seemed more engaged in the enhanced biofeedback version (over the control environment) especially when sounds were played. Users also reacted strongly when the screen shook. Participants realised there was biofeedback but did not try to adjust their breathing or heart rate to see how it affected game-play. In short, indirect biofeedback seemed effective and more engaging than the control (a game level with no biofeedback).

However we are reluctant to recommend further use of the Wild Divine technology. The sensors interfered with hand control, required continual recalibration and occasionally gave unreliable data. While for our research these limitations were acceptable (although some might disagree, such as Kuikaniemi et al 2010), more recent developments such as Neurosky (Rebolledo-Mendez et al, 2009) and Emotiv (Zintel, 2008) offer more promise in terms of stability and ease of use. The Half-Life 2/ Source game engine also has implementation issues.

Biofeedback and architecture-potential uses

There are various papers and projects on using biofeedback or phobic triggers in virtual environments to either expose and cure phobias, or to develop understanding of oneself, or of others, but we have not encountered discussion on how biofeedback can be used to enhance (digital) architectural appreciation and understanding.

One potential use is for personalization. Digital environments have been criticized for being sterile, and empty, lacking personality, individuality or warmth (Green, 1996; Minocha and Reeves, 2010). Biofeedback could augment and provide individual personalization, adding in unique lighting affects, sounds, or other details relating directly and dynamically to the participant's physiological states.

Biofeedback could also personalize social virtual environments, where multiple people (such as stakeholders in urban design projects) are simultaneously immersed in a virtual environment. They could view or hear how others are reacting to the virtual space. Or perhaps where the virtual world is based on a real-world place, biofeedback from real world passers by and inhabitants could be fed in real-time into the virtual world.

If walking through a virtual environment triggers participants' memories or emotional attachments of the real-world place being simulated, it may be possible to colour or otherwise tag these locations in the virtual environment in relation to the biofeedback being generated. However, this does not seem accurate or reliable. Bored mental states that arise independently of the virtual environment may affect results. Non-visual (not tactile or olfactory or audio)

sensations aren't likely to be available via digital media. There may be useful applications in the evaluation of engagement via virtual environments being automatically tagged by the biofeedback of visitors (chairs, rooms or graspable objects could retain a metaphorical aura, for example), but this would be hard to evaluate in small experiments.

There is also the notion of architectural empathy. In a book entitled *Empathy and Its Development* (Eisenberg and Stronyer, 1987), a clear distinction is made between empathy and sympathy (concern for people). Despite various definitions of empathy there is a tendency for empathy to be divided into empirical empathy (by association) or empathy through feeling (also called personal empathy). Empirical or aesthetic empathy involves attributing personal qualities to people *and* to objects, such as columns etc. So one may be able to create differing architectural spaces and evaluate with biofeedback whether they elicit certain responses, but this at least initially appears a highly involved and complex situation to evaluate.

Atmospheric augmentation was carried out in the Ravensholm Wild Divine-Half Life 2 study, uniquely personalized and augmented environments could be created from varying rates of biofeedback. However, how the environment is modified might not necessarily augment the experience during play, and may not even be recognizable (let alone be considered evocative) by the participants. Another problem is that this may *gamify* and *adrenalize* the architectural experience. In other words, enjoyment comes from visceral augmentation, and a rewards system which does not necessarily relate to the architecture as designed, nor help any meaningful experience of the surroundings themselves apart from as backdrop or as *ludic affordances*.



Figure 3. *Qumulus* interactive real-time weather system using *Quest 3D*

Perhaps more effectively, biofeedback may be used to augment the overall atmosphere, or even climate. Recent technology has seen the development of real-time interactive weather simulation, and they could also be controlled by biofeedback (Figure 3). However although this external environmental data may add to user engagement, this information is not necessarily relevant to

the individuals' goals and emotional state. A more architecturally appropriate interaction metaphor might be linking visual signs of pollution and decay to the overly excited biofeedback, the more excited the player the more quickly the building decays.

Extrapolating from game mechanics, we could leverage biofeedback states that are generated from excitement (or boredom) in games to colour or otherwise alter digital spaces as a reward and feedback system. Architecture can be seen as a complex symbolic relationship of path and centre, of detail at places of rest (such as in formal seating areas), and subdued detail where circulation is important (such as corridors and staircases). If the participant understood a space was designed more for rest than for activity and acted accordingly (such as slowed down their heartbeat and GSR to appropriate levels) the environment could change to reflect their physiological harmony with their surrounds.

Such a scenario might not work so well in a game environment where it would not be clear how activity based biofeedback would give either the participant or the viewer a better idea of how the participant is affected by the architectural quality of the space itself and not just by responses to located events. However it may be appropriate for sacred or mythical spaces, where the calmer the participant is, the richer the interaction afforded, increased environmental details, avatars develop supernatural or mystic powers, or religious beliefs take virtual form.

It is also possible to use biofeedback as an evaluation mechanism, such as evaluating spatial awareness, and detecting potential differences between spatial designers and the public. This technology might be able to detect developing spatial awareness in student designers, and where and when spatial awareness impinges on general awareness in virtual environments.

Biofed architecture could track phobias (also known as negative engagement in virtual reality literature). Where people encounter phobias near architectural points in time and space, their negative phobias can be visibly recorded and aggregated. The digital model could be 'sprayed' with an aggregated spray of phobia colour. We note here it may be difficult to aggregate phobic areas or even locate the spatial or symbolic phobic triggers. Furthermore, trained psychological help may be required to create, calibrate and adjust the environments as well as ensure that the test environments pass ethical and medical clearance and are used safely and effectively.

Conversely, positive engagement could also be tracked: significant points of interest (indicated by pauses, and by heightened or lowered rates of biofeedback, and perhaps camera tracking of postural change, or tracking of eye gaze) could be recorded.

Finally, filtering environmental detail through biofeedback may both

virtual and augmented reality projects, such as lifeClipper (Torpus and Bühlmann, 2005). Through the head mounted display, participants saw vague and coloured video characters as they walked through Basel, but through oddly shaped stencils. Biofeedback could have affected the perimeter and clarity of the augmented reality objects, the calmer the walker; the higher the resolution clarity or viewing window of the augmented display object or video. This project also featured pressure sensors incorporated in soles to wear in one's own shoes for tracking walking behaviour, but it could also be used to augment the excitement level in the augmented environment.

At a simpler level, biofeedback can be used to affect territorial awareness, for example, more excited states could increase or diminish the field of view, and this could have significant benefits for large-scale projected environments such as CAVE UT.

Methodological issues

Are there currently accessible, effective and accurate devices to measure biofeedback? What can we measure, react to, and creatively leverage when implementing individual and group biofeedback, which are appropriate to the architectural domain? Are there any advantages or disadvantages to the use of biofeedback and can we ascertain them by trial evaluations?

The following products, Neurosky, Emotiv, and Wild Divine have been selected as the most accessible and widely used biofeedback devices for recent virtual environments. For the sake of simple architectural experience tests, we argue that biofeedback can be applied in terms of understanding the self, the environment, or other (fictional or real) participants' reactions to the environment. However, the variety of responses possible, the lag, the calibration required, and the indirect and vague nature of the biofeedback have convinced us that for architectural testing purposes it would be difficult to conduct tests using biofeedback to ascertain architectural empathy of form or material.

Secondly, we suggest that indirect biofeedback used to increase the sense of trepidation or excitement of the environment is best employed in games (or perhaps in social worlds), however there is potential to assess serenity and contemplation in sacred spaces. Thirdly, using indirect biofeedback to personalize the environment and recognize the attitude through physiological state of others is interesting, but difficult to evaluate in smaller test environments of shorter duration. For measuring subjective responses, using a control group to test comparative results in task performance does not seem appropriate.

Architects may be more interested in whether participants find the modified environment is more responsive (in a positive way), with more character, more appropriate to what is simulated, and more interesting. They may also

be interested in whether the modified environment has a more engaging sense of territoriality. For example, changes between calm and excited biofeedback states could affect the field of vision and the lighting condition. Finally, the participants could also be asked which of these biofeedback-influenced factors have the most natural mappings (i.e. the interaction metaphors are most appropriate).

Conclusion

What is innovative about biofeedback applied to architecture and why is it significant? As far as we know, there is no convincing and through review of how biofeedback, and indirect biofeedback in particular, can be usefully applied to architecture. While there are increasing numbers of papers on biofeedback applied to games, such research must be critically reviewed before being applied to digital architecture, for the two fields differ so greatly.

This paper explored the imaginative and atmospheric use of real time biometric feedback within interactive digital environments but particularly for architecture. We suggest five main areas of applications for the above type of biofeedback (indirect biofeedback based on changes in physiological states) for digital architecture. Participants could indirectly colour their surroundings, which may afford them more insight into the world around them, their interactions with it, or the progress and experience of other participants. In terms of object creation, more uniquely personalized and engaging environment elements (also known as externs) could be directly or indirectly created from biofeedback. Atmospheric-affecting biofeedback may augment and enhance a sense of inhabitation. Biofeedback could also be used to contextually filter and display information so that a user is not overloaded with extraneous information, or, conversely, observant and more empathic participants could be rewarded with more information. Indirect biofeedback could also help tracking of participants (of phobias – also called negative engagement – and positive engagement).

These ideas may be of interest to those keen on creating more engaging virtual worlds, those interested in whether digital simulations can better approach the richness of real world places, and those curious in indirect interaction metaphors for experiencing places. Biofeedback may help those who wish to create not just simulations of religious, revered and historic architectural sites, but those who also wish to convey a sense of the experience of various audiences who have visited them.

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PRELIMINARY EXPERIMENTS OF OPENSIM PERFORMANCE EVALUATION FOR VIRTUAL DESIGN STUDIOS

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Abstract. This paper presents a technical performance evaluation of OpenSim as an alternative platform to Second Life, for virtual design studios. A number of issues that are critical for conducting virtual design studios were investigated through a series of tests and reflections from a Visual Training class. A performance test was also carried out in order to test server load against computer memory. These findings will provide valuable understanding to academics looking to use similar environments to Second Life for virtual design studio.

Keywords. 3D virtual worlds; OpenSimulator; virtual design studios; performance evaluation.

1. Introduction

In the field of Architectural Design Education, there have been researches about using 3D virtual worlds notably Second Life in Design and Design Education (Abdellatif and Calderon, 2007; Hernández Ibáñez and Barneche Naya, 2007; Tan and Lim, 2010). We have conducted virtual collaborative design studios in Second Life since 2008 (Gu et al, 2009; Nakapan et al, 2009). Our students were able to collaborate across the continents on design projects. Nevertheless, it was identified during the collaboration that Second Life has the following limitations, which have significantly compromised the establishment of virtual design studios, and limited students' design and learning activities in the studios. These limitations include:

- Initial set up cost is 700USD, with maintenance cost of 1,770USD per year (Educational/Non-Profit Discount will be removed from January 1, 2011 (Har-

risson, D.,2010)),

- an island size is limited to 256*256 sq.m.,
- the maximum number of concurrent users is 100 avatars per island, with effective number being only 30-40 avatars,
- the maximum number of prims allowed on an island is 15,000. However, only half of the maximum number is recommended for efficiency,
- the largest size of each prim is 10 meters,
- an image file or texture upload costs 10L each (around 1.45 cent),
- creating user account in bulk is prohibited.

In 2007, Linden Lab has released its viewer source code. Consequently, OpenSimulator, often referred to as OpenSim has emerged as an open source server platform for hosting virtual worlds. Further, it provides much greater flexibility in customizing the virtual worlds that were not possible previously in Second Life. Since then, OpenSim, even though in its early development stage, has been applied in the practice of virtual worlds, i.e. OSGrid (“OpenSimulator grid list”, 2010). Recently, it has gained popularity among academics as an alternative to Second Life (Hu, 2010). It has the potential to open up new opportunities for design and collaboration since users, at lower cost, can have more control over the environment, such as creating and owning more islands, customizing the islands such as changing the shape and elevation of land (terraforming), building limit and access right, enriching designs in the virtual worlds such as having free upload of texture files, etc. A recent study on the topic “Comparing OpenSim with Second Life” (2009) has identified that OpenSim has strength and potential over Second Life, regarding cost and object building. However, these issues are not adequately explored, especially in the context of conducting virtual design studios. The user requirements for these studios are quite different from average users’ of the virtual world. Therefore, this paper looks into specific issues of OpenSim that are related to virtual design studios, i.e. effectiveness in setting up such platform and changing environments in the virtual world. Our investigation evaluates and demonstrates how OpenSim can be used as an alternative platform for virtual design studios, through experiments and our experiences from a Visual Training class in OpenSim. The findings will provide valuable understanding to academics looking to use similar environments to Second Life for virtual design studios.

2. Background: System architecture of OpenSim

Standalond mode V.S. Grid Mode: OpenSimulator can operate in one of the two modes: standalone or grid mode (cf. Figure 1) (“OpenSimulator Configuration”, 2010). In the standalone mode, a single process handles the entire simulation, which consists of region simulator and backend services (user,

asset, inventory, ...). In the grid mode, a common service can be run on one machine, while region simulators can be run on other machines using the same set of common services. The standalone mode is easier to configure. However, the grid mode is scalable according to the number of users. An address of a simulator is referred to as a URI (Uniform Resource Identifier).

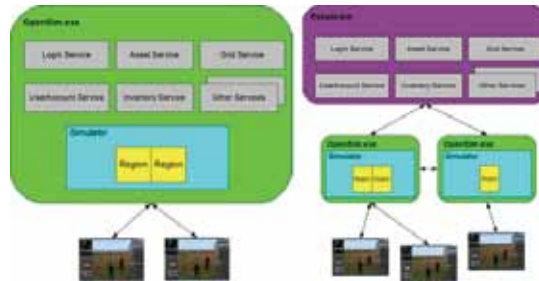


Figure 1. System Architecture of OpenSim: Standalone mode v.s. Grid mode
(illustration adopted from opensimulator.org)

Hypergrid can be thought of as a virtual world hyperlink (“The OpenSim Hypergrid”, 2010). It is an extension of OpenSim, which can be applied either in the standalone mode or the grid mode. It allows a seamless transfer of agent between sims. Thus a user logs in on to his sim and can transfer to another sim while having his own set of inventory.

3. OpenSim performance evaluation for virtual design studios

This paper aims to examine the effectiveness of OpenSim as an alternative platform for virtual design studios. Based on a list of issues identified from our previous design and teaching experiences in Second Life, we conducted a series of lab tests to investigate the following technical issues in OpenSim:

- a. Issues related to server setup, configuration and performance
 1. Setting up OpenSim on common lab PCs,
 2. setting up a web interface to facilitate the creation of user accounts,
 3. linking to another Sim using Hypergrid,
 4. changing maximum prim limit allowed on each island,
 5. server performance test (this issue will be explored in Section 4).
- b. Issues related to changing environments in the virtual world
 1. Creating a mega-region (continuous islands merging together),
 2. importing archives (terrain, island, and inventory),
 3. creating a group of users,
 4. dividing land,

5. creating large prims,
6. uploading texture files.

These issues are likely to be encountered by both the average users of virtual worlds, and students in virtual design studios. For issues related to server setup and configuration, one may adjust its environment in order to suit the purpose of the design studio according to available resources, i.e. making sure the server can handle a given number of avatars, and the students not building beyond the limit of available RAM, etc. For issues related to changing environments in the virtual world, one may change environments to suit each assignment, i.e. changing the terrain form according to the purpose of the assignment, providing enough parcels for students to build on, etc. This section will first briefly introduce the Visual Training class and its outcomes, followed by the lab tests and/or experiences from the Visual Training class.

3.1. THE VISUAL TRAINING CLASS

The Visual Training class was offered to 15 first year architectural students during October 2010 - January 2011. The objective of visual training is for students to develop the skill and understanding of artistic composition theories, starting from the arrangement of 2D elements and developed into more complex 3D designs. This small-scale class with simplified design and modelling tasks is a perfect vehicle allowing us to evaluate some of the technical performance issues of applying OpenSim in design education and preparing us for setting up full-scale virtual design studios scheduled for June 2011.



Figure 2. Three assignment examples from the Visual Training class

By the end of November 2010, three assignments were implemented by the students (cf. Figure 2). The first one is called “A star’s avatar” in which students were asked to use modelling and graphic design tools in OpenSim to create avatars resembling a star or celebrity. The second assignment is called “Crop circle”; the students designed a 2D visual pattern with dots, lines and planes. The third assignment is called “From 2D to 3D”, each student was

given images of a floor plan and four elevations of a simple house. They were then asked to design and simulate a house using the native design and modelling tool in OpenSim. These three assignments utilised a range of design skills and allowed us to test a wide range of design and modelling tools in OpenSim for supporting design in virtual design studios. The assignments show that students have developed and demonstrated basic skills in design and modelling using OpenSim.

3.2. ISSUES RELATED TO SERVER SETUP AND CONFIGURATION

1. Setting up OpenSim on common lab PCs. OpenSim can be run on two platforms, (1) Window with Microsoft .NET framework and (2) Unix-Mono. The set up test was done on two common lab PCs (Window XP, Intel Core2 Quad@2.33GHz, 4GB of RAM) located at the lab of Rangsit University. The versions of OpenSim tested in the lab were both an official version (currently 0.7.0.2) and a spin-off version called Diva Distro (currently r13981) (“Downloads for diva-distribution”, 2010). This latter version distributed as Standalone Hypergrid pre-configured, was found easier to set up and update.

2. Setting up a web interface to facilitate the creation of user accounts. Diva Distro is also delivered with a built-in web interface called Wifi. The Wifi supports (1) account creation, optionally controlled by the administrator, (2) configurable default avatars for new accounts, (3) account updates by both users and the administrator, (4) account deletion by administrator, (5) password recovery via email, and (6) simple user inventory management. For the Visual Training class, students were asked to register their account on the Wifi webpage. After approval from the administrator, all students were able to login to the simulator.

3. Linking to another sim using Hypergrid. Hypergrid is an alternative way of scaling the standalone sims since running an OpenSim in the grid mode requires at least two servers. It also allows avatars moving from one sim to another.

A test has been done linking three standalone sims together, two lab PCs and a sim running on a home server. Three avatars from different sims then were able to meet successfully on a particular sim.

4. Changing maximum prim limit allowed on each island. We have experimented with limiting the number of prims allowed on each island via RegionConfig.ini file. Even though this feature is available on OpenSim, it is found non-functional, since students could build beyond a given limit, which can significantly slow down the navigation and collaboration in virtual design studios.

3.3. ISSUES RELATED TO CHANGING ENVIRONMENTS IN THE VIRTUAL WORLD

Creating a mega-region. Similar to Second Life, a regular size of a region on OpenSim is 256*256 sq.m.. However, a larger region can be achieved by combining different standard regions. Such a region is called mega-region, which has to be in rectangular or square shape, either 2*2, 2*3, 3*3, ... The support for large regions in virtual worlds is essential for large-size virtual design studios, and design projects that require large sites. Setting up a mega-region follows the rules below. Regions will have to begin at South West and end at North East. The position of a region is identified by its Cartesian coordinate (x,y). And a different region needs a different port. For example, the centre of the grid is considered as the coordinate of the first region (1000,1000), the region name is SW, and its port 9000. A 2*3 simulator was designed and successfully implemented for the Visual Training class.

Importing archives. *Changing the terrain form of an island using .raw files:* An island's shape in OpenSim can be changed by uploading a different .raw file to the system. For the Visual Training class, we have used a flat terrain file, since it was easier to construct on.

Importing an island using .OAR files: An entire island (its terrain, objects, scripts, ...) can be imported or saved using .OAR file (OpenSim Archive). For the purpose of the Visual Training class, an island from OpenVCE project provided by the University of Edinburg (Tate, A., et al, 2010) was used in order to quickly setup the virtual campus. It provides an ambient space of a virtual campus, with buildings, exhibition areas, educational items, and a large auditorium where online lectures take place.

Importing inventory items using .IAR files: An inventory folder can be imported to OpenSim using .iar file. It can be very useful for beginner students because a collection of design and other useful virtual worlds elements (objects, textures, landscape items, clothing, etc.) can be provided to each student for them to begin with. It is found that a large .iar file can make the server unstable.

Creating a group of users. A group in OpenSim allows users in the same group to contact each other and share resources. A group can be created and students can join the group at no cost (it costs 10L in Second Life). A group module was implemented and tested in the class, which has been proven effective.

Dividing land. Land of a large area in OpenSim can be divided into parcels as small as 16*16 sq. m.. They can then be sold or given away to individual users via a system of Estate. This capability is very important for different students

to have different control rights over their own sites on a shared island within a virtual design studio. However, the division of the land should still be carefully coordinated. For example, in an assignment from the Visual Training class (“crop circle”), when students were given the right to divide and claim land themselves, it can become quite chaotic. The parcels were not of the same size, overlapping each other. In another assignment (“from 2D to 3D”), lands were already centrally divided into small parcels before being assigned to students. In the latter case the site is better organised, but can also become quite static. The merely square or rectangular parcel shapes can sometimes limit students’ design possibilities.

Creating large prims. Prims in OpenSim could be created as large as 100 meters, using other viewers (Imprudence Viewer, Hippo Viewer,...) as opposed to the limit of 10 meters when using Second Life viewer. Students therefore have more opportunities and increasing flexibility in design and modelling.

Uploading texture files. Due to the costs associated with texture upload in Second Life, in our previous collaborative design studios students did not have adequate experiments on applying textures in enriching designs; some were limited to other free design elements such as colours and transparency only to explore design options. Textures can now be uploaded into OpenSim at no cost. Students could freely explore the use of textures and modify them as frequent as necessary in their design. Some lecture slides were also uploaded into inventory as textures and then showed on the virtual screens to the class.

4. OpenSim server performance test and results

OpenSim server performance is a very complex issue. It can be affected by a combination of the following matters: the number of prims on a region, number of regions, number of concurrent avatars, network quality between server and viewer, RAM, processor, etc. So far there is no precise information about the recommended hardware specifications (“OpenSimulator Performance”, 2010). A number of concurrent users that the server can handle is also a critical question. In our case, we characterise “active users” as avatars who model, communicate and collaborate, navigate, ... constantly. To evaluate the performance of the server, we organised a case study to test the OpenSim server load against memory, to see the number limit of avatars/prims in relation to Frisby’s evaluation (Frisby, 2009).

The test environment for the case study was our lab PC server (Window XP, Intel Core2 Quad@2.33GHz, 4GB of RAM, MySQL database). We used the latest Diva Distro as an OpenSim platform. The experiment involved using a

server of 3*3 regions (nine islands), active users built the maximum number of prims on one region after another until they all lagged (avatars could no longer move):

1. The 30 active avatars logged in into the system with 2 observer avatars.
2. The 30 active avatars gathered on SW island. They built 17,773 prims. The system lagged.
3. The 30 active avatars gathered on S island. They built 10,057 prims. The system lagged.
4. The 30 active avatars gathered on Central island. After tp, 3 avatars logged out unexpectedly. They built 5,012 prims. The system lagged.
5. Only 17 avatars could tp to SE, all the rest had to logout and re-login. The 30 active avatars gathered on SE island. They built 15,614 prims. The system lagged.
6. Most avatars could not tp to NE island, they had to logout and re-login. They built 54 prims. Then a server error was observed.
7. The experiment ended.

Table 1. Memory consumption of OpenSim in the server performance test

Description	Memory (MB)
A base cost of 200mb	200
Size of all textures in an average region is around 50mb: 50mb * 9 regions	450
30mb per 1,000 primitives	
– SW (17,773 prims)	533.19
– S (10,057 prims)	301.71
– C (5,012 prims)	150.36
– SE (15,614 prims)	468.42
– NE (54 prims)	1.62
– N, W, NW, E	-
50mb per concurrent user and double the sum if running under Mono (50mb*32 concurrent users .)	1,600
	3,705.3MB (3.62 GB)

After a calculation based of Adam Frisby's description, the system consumed 3.62GB of RAM. The server however, had 4GB of Ram installed, with 3.49GB of RAM left after deduction of those consumed by the OS. The performance test results (cf. Table 1) echo and extend Frisby's evaluation to provide a rough

calculation for memory consumption in using OpenSim. And the server can effectively handle 32 avatars, if there were not excessive amounts of prims on the region. The result repeated our earlier experiment on the same server using SQLite database and an earlier version of OpenSim, which handled 25 avatars. These results show that, while a later version of OpenSim seems to handle more concurrent avatars, the number of maximum prim limit is closely related to the memory. Consequently, one can predict that with twice as much RAM, one could expect twice as much prims and textures. However, this presumption of linear progression still needs confirmation. As for the texture, according to Liang, Motani and Ooi (2008), the median texture size over all three regions in their research was 95 KB. We can assume that 450Mb. of RAM can handle around 4,850 textures, which can cost up to 70USD in Second Life – not so significant saving.

5. Summary and the future

This paper presents a series of preliminary experiments to evaluate the technical performance of OpenSim for virtual design studios. Overall, based on a small-scale class with simplified design and modelling tasks, OpenSim shows potentials to serve as an alternative platform to Second Life for virtual design studios with no additional cost on the platform. In our case, this is a saving of 20,700 USD per year due to the switch from Second Life to OpenSim. OpenSim responded satisfactorily to most of the issues investigated in the Visual Training class. The open source nature of the platform also provides academics and students with greater control over the virtual environments. It is this increasing level of customisation and flexibility that distinguish OpenSim from current virtual world platforms and will potentially improve the design and learning experiences in future virtual design studios. The platform will be applied to a full-scale design studio scheduled for June 2011 - broader and more in-depth issues will also be explored.

However, being in its infancy stage, some of the features, such as setting prim limitation for a region did not work. Nevertheless, Diva Distro was proved to be very effective for a small-scale design and modelling class, and with future refinements we believe these flaws will be overcome. Our performance evaluation can provide indications for academic institutes to plan and scale the simulators according to their available resources.

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SIMULATING 3D ARCHITECTURE AND URBAN LANDSCAPES IN REAL SPACE

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Abstract. In the present research, we have developed a system by which to simulate three-dimensional architecture and urban landscapes in any outdoor space. As the basic AR environment, we used Vizard running on a laptop PC, where the urban model component, location tracking component, and image display component work together using original Python scripts. For the urban model component, digital maps data were converted. For the location tracking component, portable DGPS and a high-precision gyroscope were introduced in order to minimize the locational error. For the image display component, optical see-through HMD was used. Stereovision was also realized with the functions of GPU on the PC. A walking experiment was performed to test the proposed system on a redevelopment plan for our university campus.

Keywords. AR; GIS; DGPS; Optical see-through HMD; Stereovision

1. Introduction

At present, landscape simulation using CG is widely used in the field of architecture and urban planning in order to produce photorealistic images of proposed plans. Most of these images must be viewed on printed materials or on a screen presentation in a room. However, spatial recognition by planar picture expression can be at variance with the spatial recognition of real space.

For example, most architectural regulations (e.g., volume control) are designated based on numeric criteria. However, the experiment of the present study reveals that even experts cannot accurately estimate architectural volume from a three-dimensional image presented on a screen. In order to understand the construction project exactly, visual pseudo-recognition at the actual location can be effective for both experts and general citizens.

However, augmented reality (AR) technology is growing rapidly, and

advanced applications are beginning to be used. Systems to supply text-based information within the view of actual places have attracted the attention of the public^{*1}, whereas the use of systems to supply three-dimensional images remains limited to indoor experiments or trials in a confined space.

In the field of information technology, the experimental system using RTK-GPS and HMD was proposed in the late 1990s (Feiner et al, 1997). Then, in the field of architecture and urban planning, various studies have also been performed by the advanced researchers in the world (Wang and Schnabel, 2010). In Japan, Onohara and Kishimoto (2004) used the immersive HMD in the experimental room to evaluate street landscapes virtually. Kakuta et al (2008) imaginarily reconstructed the ancient capital “Asuka-Kyo” landscape on the site by using RTK-GPS and video see-through HMD. Recently, many studies using ARToolkit can be found to overlay virtual models on the video images based on the makers located in real space (Yamada et al, 2008; Kunori and Watanabe, 2010). Similar to the evolution of CG technology, these farsighted researches are committed to the overlay of photorealistic images for exact and natural video images and do not enable users to walk around freely. Kawaguchi et al (2006) studied the movable system using Tablet PC and DGPS, nevertheless he pointed out the problem of taking time to modify locational errors of overlaying images.

2. Objectives

The purpose of the present study is to develop an AR system that can simulate three-dimensional architecture and urban landscapes at any location in outdoor spaces, not only depending on high-precision sensing devices, but also introducing a manual function to interactively correct locational errors with reference to the existing facilities. Specifically, the proposed system is implemented using three components, namely, the urban model component (GIS / CG), the location tracking component (GPS / gyroscope / game controller), and the image display component (HMD / stereovision), which work together using computer code developed for this project.

3. System configuration

The proposed system is shown in Figure 1, and the elements of the three components of the system are shown in Figure 2. The laptop PC and peripheral devices are installed on a backpack frame, which enables the system to be carried by the operator. The system weights 8.4 kilograms.

In terms of software, Windows XP is used because old and new elemental technologies must be combined, and Vizard is used as the AR development

environment. The computer code consists of scripts written in Python as an object-oriented programming language.

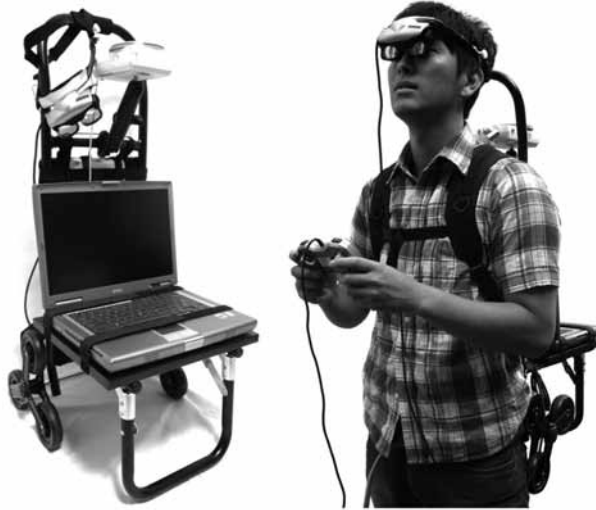


Figure 1. Proposed system

3.1. URBAN MODEL COMPONENT

For the case in which position markers or magnetic sensors installed in the local area are used to obtain locational information of viewpoint for displaying the specific three-dimensional model, it is sufficient to use the relative coordinate system. However, for the case in which GPS is used to obtain locational information over an extensive area, three-dimensional models should use the official coordinate system.

In the present study, we used the official digital map data developed by GSI (the urban foundation, e.g., roads, railways, and public facilities) and the commercial digital map data (additional information, e.g., office buildings, apartments, and private houses) together as the fundamental locational information. However, these data sets use individual data formats and cannot be loaded directly into the AR environment. The geographic information system (ArcGIS) is used to convert the data to the proper format, and the data are also modified and complemented to fill in incomplete areas from ArcGIS by using orthographic high-accuracy aerial photo (resolution: 8 cm).

Since digital maps are basically two-dimensional data, the digital elevation data (DSM/DTM) obtained by airborne LIDAR are used as height data. The DSM are the three-dimensional coordinate data of the surface of the ground, including the effects of construction, according to the recording density with a horizontal resolution of 2.5 m. The DTM also include three-dimensional coordinate data of the terrain in which the effects of construction are removed based on a mesh density of 5 m. Architectural volumes are estimated by assigning differences in average z values of the DSM and DTM included within each polygon of architectural components in the two-dimensional map.

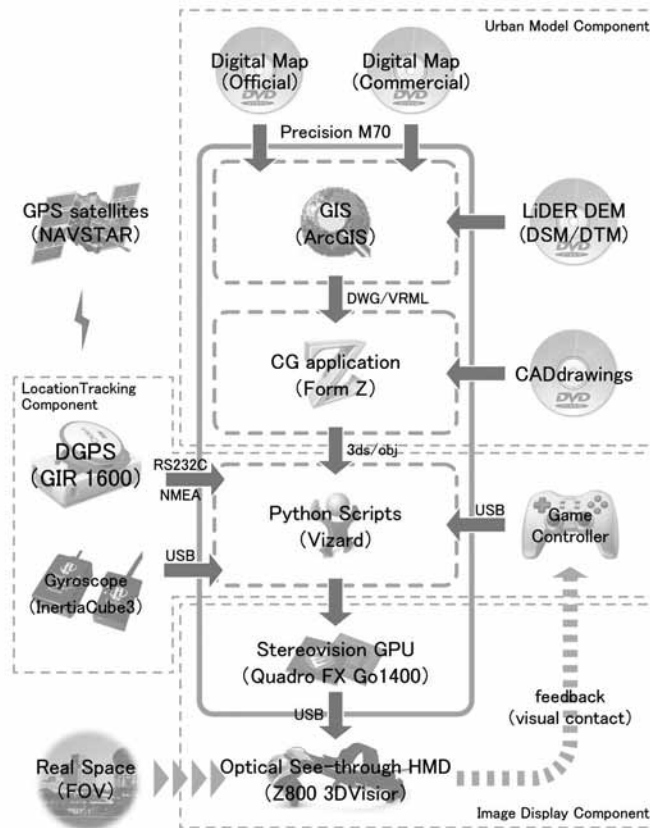


Figure 2. Elements of the proposed system.

In order to complete the three-dimensional urban model, the versatile DWG/VRML files exported from ArcGIS are imported into the CG application (Form Z). After the DWG/VRML files are combined with the data of the newly planned buildings designed based on CAD drawings, all of the files are converted to the 3Ds/obj format, which can be loaded into the AR environment.

3.2. LOCATION TRACKING COMPONENT

High accuracies are required in order to measure the viewpoint and eye direction of the system wearer so that three-dimensional urban models of images can be overlaid on the real space. For viewpoints, popular GPSs are not sufficiently accurate. A portable Differential GPS device (SOKKIA GIR 1600) is introduced in order to minimize the locational error. The GIR1600 realizes the locational accuracies within 1 m and exports longitude and latitude information based on the standard NMEA format via a legacy RS232C interface. The original script is prepared in order to open the RS232C port, read NMEA records, translate these records to the official coordinate system^{*2}, and pass the records to the viewpoints of the three-dimensional urban model.

For the detection of eye directions, the gyroscope initially attached to the HMD (described later herein) has poor sensitivity and does not provide sufficient accuracy. As with the case of locational information, a dedicated gyroscope (Intersense InertiaCube3) is introduced in order to minimize the directional error. InertiaCube3 realizes an RMS accuracy of 1 degree in the yaw direction and 0.25 degrees in the pitch and roll directions and exports this information via a USB interface. In the developed script, although the correction of declination according to the results of geomagnetic measurement^{*3} is taken into account, the results are also passed to the eye direction at the viewpoint.

However, there are limitations to the accuracies of sensing devices. In addition, the errors are also included to some extent in the constructed three-dimensional urban model, even though the model is made from the official data. Therefore, it is impossible to closely match visual images to the real space at any time. In order to address this problem, a manual function to interactively correct the viewpoint and eye direction, a game controller is incorporated into the system.

3.3. IMAGE DISPLAY COMPONENT

Video see-through HMDs are widely used in the recent studies on AR in attempts to effectively combine the physical field of vision and the gener-

ated virtual images. However, using video see-through HMDs for the purpose of walking freely in outdoor spaces is dangerous because video see-through HMDs completely obstruct the physical view of the operator. Therefore, an optical see-through HMD (eMagin Z800 3DVisor ST) is used in the present study. The resolution of the 3DVisor is 800×600 pixels, and the generated virtual images are overlapped transparently through half-mirror glasses. That is, the physical view required for walking is ensured, while the background, which should be hidden by generated images in nature, can be seen at any time. Therefore, there is no sense of processing contextual occlusion between real substances and virtual objects. In addition, at present, it is impossible to provide a sense of high immersion because the viewing angle of the optical see-through HMD is not of sufficient width as compared to the viewing angle of the human eye. These characteristics are unsuitable for achieving high-quality images, but are acceptable for assisting in the spatial recognition of real space.

In order to take full advantage of the binocular HMD, stereovision is also investigated in order to provide depth perception to the three-dimensional urban model. Stereovision technology has been used in the field of computer games, but these games are only used on the desktop computer systems. Few laptop PCs realize stereovision using the GPU function on a PC. After several trials, the ability to use a specific stereovision driver on the GPU (nVIDIA Quadro FX Go1400) installed in a legacy PC laptop (DELL Precision M70) is confirmed.

4. Walking experiment

A walking experiment was performed to test the proposed system on a redevelopment plan for our university campus. The 2.6-km² site is almost flat and contains more than 200 buildings. A bird's-eye view of the site is shown in Figure 3, which shows the three-dimensional urban model prepared for the experiment.

A participant wore the system and walked freely about the campus. Based on the experimental record, the current landscape view of his eye direction at location P, the display images of binocular vision produced by the system, and the participant's actual field of view through the optical see-through HMD are shown in Figures 4 through 6. As shown in Figure 4, a new research building is currently under construction, and the landscape view after the completion of construction can be confirmed through the HMD.



Figure 3. The three-dimensional urban model.

The record of the operation of the game controller by the participant associated with walking is shown in Figure 7. The viewpoints were generally measured in the correct positions, which verifies the accuracy of the proposed system. However, GIR1600 returns 0.0 for the longitude and latitude values when the signals cannot be properly received, for example because of being in the shadow of a building. As a result, the display images were momentarily jumbled. The participant more frequently adjusted the yaw/pitch/roll, as compared to the position. That is, with respect to spatial recognition, errors in eye direction are more bothersome than errors in viewpoint.

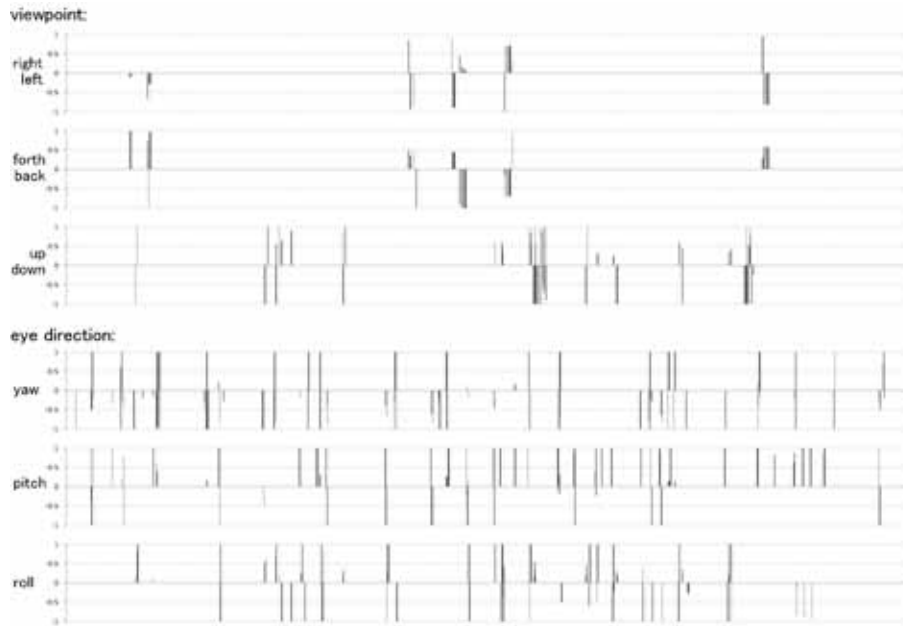


Figure 7. Record of operation of the game controller.

5. Conclusion

Unlike CG and VR, AR requires position adjustment between real space and virtual space. In the present study, we developed a system that can be used extensively in outdoor spaces by integrating advanced devices and manual functionality to correct locational errors according to an existing three-dimensional urban model. A university campus with spaces that are under development was selected as the subject of a walking experiment. However, landscape simulations using this system can be used not only for currently nonexistent features, but also for existent features that can't be seen. It may be used to confirm the old-time view of city landmarks (e.g., church steeples or distant mountains) recently hidden by tall buildings.

The prototype system is heavy, primarily because of the use of a DGPS device and a legacy laptop PC that supports stereovision. The size and weight of these components are expected to be reduced as advanced GPS and 3D technologies become more commonplace. However, the stereovision of the prepared three-dimensional urban model provides little information regarding depth perception, and much more detail is required in order to improve the system. Since the optical see-through HMD does not have high luminance, it

is difficult to see in sunlight, but the HMD was adequate for use in the evening and on cloudy days.

With respect to the necessary computer scripts, an automatic function to correction viewpoints according to the adjacent data is required to prevent display images from jumbling when the GPS device cannot pick up a signal. In addition, at present, the system loads all of the data of the three-dimensional urban model upon start-up. In the future, a mechanism to separate and load data individually as needed is expected.

Endnotes

1. For example, “Sekai Camera”, which was introduced in 2009, attracted a great deal of attention as a practicable AR application that can be used on the iPhone.
2. <http://vldb.gsi.go.jp/sokuchi/surveycalc/algorithm/bl2xy/bl2xy.htm>
3. <http://vldb.gsi.go.jp/sokuchi/geomag/>

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We would like to acknowledge the contribution of Mr. Yoshitaka Kunori, a graduate student at University of Tsukuba. The present study was supported by the “New Developments of Spatial Analysis Methods Combining Geographic Information Science and Urban Engineering” Grants-in-Aid for Scientific Research (KAKENHI) in Japan.

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FIRST STEPS OF THE AUGMENTED DESIGN STUDIO

The interconnected Hybrid Ideation Space and the CI Loop

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Abstract. Professional or school design studios are essential environments for design supporting free exploration of materials and representations, analogue or digital. New technologies have moved into the studio with mixed results. Paradoxically, the use of portable computers, using Internet as collaboration channel, has actually *individualized* the design work and limited the support to co-creation, reinforcing individual work. The Augmented Design Studio argues for the implementation of hybrid technology, such as the Hybrid Ideation Space (HIS), in the design studio to compensate for the absence of collective local or remote efficient ideation space. This paper presents a case study showing the primary results of distant synchronous and asynchronous design collaboration supported by the interconnected HIS during an ad-hoc project and assessed by the improved Collaborative Ideation Loop (CI Loop) methodology. The HIS was installed in two universities located in different countries. We ran a research protocol in the format of a design *charrette* where two teams (team a: two architecture students, team b: two industrial design students) participated in the ideation of a bus shelter. This case study shows that teams were able to co-design while they were virtually “teleported” into each other’s representations.

Keywords. Design studio; hybrid approach; Collaborative Ideation Loop; telepresence; Hybrid Ideation Space.

1. Introduction

The design studio is key for all design disciplines supporting free exploration of materials and representations, analogue or digital, without constraining interfaces, and within the strict constraints of the project. The physical (sensual) character of this exploration and the collaborative nature of the studio are the levers of creativity in this environment. New technologies using Internet as collaboration channel, have actually limited co-creation and individualized the design work. We are focusing here on simultaneous co-creation, or co-design, as opposed to cooperation where teammates work individually at *exteriorizing ambiguous concepts*, then regroup as a team to *communicate* their concept to each other and analyse it together. The Augmented Design Studio implemented the Hybrid Ideation Space (HIS) in the design studio as collective local or remote design space. This augmented approach keeps the user ahead of a fully digital approach. The goal is to serve the designers as they are, augmenting their acquired capabilities while recognising their cognitive limits. The HIS was developed in 2007 (Dorta, 2007) as a hybrid technology (analogue and digital) to allow designers to be *inside* their representations. In previous studies (Dorta et al, 2009; 2010) the HIS appeared to enhance the collaborative ideation process in face-to-face situations. This paper presents a case study showing the primary results of distant collaboration supported for the first time by two interconnected HIS installed in two distant universities. We ran a research protocol in the format of a design *charrette* where two teams of two students, from two disciplines (architecture and industrial design), participated in the ideation (conceptual design) of a bus shelter. They worked synchronously and asynchronously in different time zones. To assess the collaborative ideation (CI) we used a methodological and theoretical framework we previously developed, but improved further in this study: the Collaborative Ideation Loop, or CI Loop (Dorta et al, 2010). This case study shows that teams were able to co-design while they were virtually *teleported* in their shared representations. The co-creation was effective enough to achieve special moments of silent co-design, designers communicating graphically through the representation, each following and reacting to the other's suggestions. The CI Loop could provide better understanding of the collaborative ideation process.

2. Design studio issues

Graphic ideation should not be confused with graphic communication. Ideation is an active formative process related to idea generation and maturation, usually considered as visually *talking to oneself*. Graphic communication is a

passive explanatory process that presents fully formed ideas as visually *talking to others* (Marshall, 1992). In the context of CI, ideation conversation is collective and can be synchronous (considered co-design: doing simultaneously the task), or asynchronous (considered cooperation: putting together individual tasks) (Achten, 2002). Passive communication in the context of collaboration is reduced to presentations, done locally or remotely. These distinctions are important to better appreciate the CI exchanges. With the arrival of computers in design practices and the replacement of physical representations (sketches and physical models) by digital files, design studios have lost much of their ability to act as collective incubators. Two people sharing individual representation from a laptop does not replace the design studio's collective exchanges over simultaneously viewed multiple representations, and its group synergy.

For ideation purposes, traditional and digital media used in the studio can be considered in essence inadequate for ideation (and CI) because of basic problems: for the former, proportion issues of traditional sketches and models and workload of working with technical documents (plans); and for the latter, the need of a *digital know-how* (commands and interaction) and precise instructions delivering precise representations (finish and photorealistic), which is premature at the ideation stage. Designers are not able to be *inside* their sketches and models mastering scale and proportions during individual or collective ideation, while plans require information coding and decoding, hindering mental images and personal interpretation. Computers demand specialization to face the needed *digital thinking* or *digital logic* (Dorta, 2007) in addition to the design thinking. Even with a title like "Against ambiguity", Stacey and Eckert (2003) recognize that the computer offers a limited, narrow perceptual space ill-suited to ideation (*exteriorising ambiguous concepts*), which calls for inaccuracy, ambiguity and abstraction in order to foster reflexive conversation with the representations.

2.1. INDIVIDUAL VS. COLLECTIVE IDEATION

Designers frequently switch between moments of individual and collective ideation, focusing on their own or jointly resolving specific project issues. Because of the studio configuration, they can isolate from the group to converse with themselves through traditional representations (sketches and models), moving to the computer to further this individual *reflective conversation* (Schön, 1983). In addition to these media, they can do CI through real or virtual meetings. Talking is considered the first design tool (Jonson, 2005). Kvan and Gao (2004) have found that remote collaboration through chat lines, because it keeps traces, supports higher quality of design framing (addressing problem and context) than verbal communication. They can do CI locally or

remotely by phone, by chat and videoconference (e.g. Skype™), by shared online digital sketching (whiteboard) or through virtual worlds. Following up on contributions, cooperation is possible by exchanging physical information and annotations, digital files or models through electronic messages, in the local network or remotely in virtual worlds by Internet.

2.2. VIRTUAL DESIGN STUDIOS

Virtual design studios are computer-mediated environments, from simple email to collaborative virtual worlds. They adopt different metaphors, from a *desktop* to a *virtual place*. They can be centralised or distributed depending on file transfer and storage (Maher and Simoff, 2004). Originally developed on VRML, virtual environments allow collective 3D modelling and visualisation (e.g. Second Life™). This media is particularly relevant to CAD since digital models can be shared and explored through their worlds. As they are accessed through computer screens and avatar projections, the immersion felt in these virtual environments is disembodied (loss of awareness of physical self) and they do not provide the same kinds of explorations a real, physical, fully sensorial immersion can. There, avatars are used to evaluate proportions and, according to some authors (Abdellatif and Calderon, 2007), offer high perceptual and spatial qualities, and presence. They can also allow verbal and chat line exchanges. However, these environments suffer basic problems when it comes to ideation. Most of the models are made outside the world (e.g. Autodesk 3ds Max), because of 3D modelling limitations (complex shapes) and system's performance in terms of real-time rendering and interaction (Heidrich et al, 2007) to accelerate navigation and visualization. Furthermore, the real design studio exchange is imitated in a virtual world, down to reproducing the participants, bringing fundamental technical problems such as heavy calculations involved in getting an avatar to properly imitate human gestures, to moderating the collaboration, to making annotations or to sketch asynchronously only (e.g. Jung et al, 2001). In the Renaissance, once geometry was mastered, *architects* moved from the construction site to the studio, keeping crucial proximity to the project's context. Current technology allows virtual visits (Google Street View™) but without the telepresence of life size proportions (Porter, 1979), which is important to achieve a more effective ideation. Finally, the design project involves many disciplines requiring, during synchronous exchanges, representations that do not demand particular specialisation. Basic annotations through sketches combined with gestures and explanations are fundamental to sustain ideation and have been least supported by 3D modellers as seen in previous comparative studies with the HIS and traditional sketch and physical models (Dorta et al, 2009). In the

HIS, the sense of presence is maintained by real-time direct interaction with the graphical representation (sketch) supported by voice conversation. The life-size scale of the shared immersive space reinforces this sense of presence.

3. The Augmented Design Studio and the interconnected HIS

The Augmented Design Studio is based on a hybrid technology, such as the Hybrid Ideation Space (HIS), that combines the advantages of traditional CI tools augmented with the capability of technology, without reproducing or imitating them. The HIS allows co-located or remote co-design and cooperation through a media that displays the work to all, teleporting the designers in each other's representations.

Implemented in 2007 (Dorta, 2007) and assessed and compared as ideation and co-located collaboration tool (Dorta et al, 2009), the HIS permits freehand *sketching* and *physical model making* layered over in-context images, in immersion (life sized and real-time). It is a low-tech system: a tablet PC (Modbook™), a projector, an HD IP camera and a 360° immersive projection system based on spherical panoramas. The user sketches on the tablet or makes a rough scale model (in the model station) while spherical images are projected upward to a semi-spherical mirror on the ceiling and then reflected on the ceiling-mounted semi-spherical 16' diameter fabric screen. The user sketches in a normal perspective while the HIS software distorts the sketch in a spherical panorama. The tablet PC is mounted on a rotating device that allows users to always sketch in front of them inside a drawing area while they look all-around at a normal (undistorted) life-size 360° degrees perspective on the screen, thanks to the *trompe l'oeil* effect (from inside, users feel inside a 3D environment). Based in the same optical distortion, the model station uses the IP camera combined with a tiny semi-spherical mirror to capture in real-time (low fps for better transfer rates) the rough scale model while projected at life-size on the semi-spherical screen, avoiding the *Gulliver effect* (Porter, 1979), (Figure 1).

The HIS can receive up to four people for co-located synchronous collaboration under a new metaphor, the *hybrid place*, combining real and digital tools, interactions (acquired skills) and data. In order to address real practice requirement for remote collaboration, we networked two HIS. The sketch and the immersive real-time video of the model can be shared symmetrically (between two HIS) or asymmetrical (HIS and tablet, which was not used in this study). In this distributed setting, sketch data is relayed to a server that sends the information to the other HIS software while the video is accessed directly from the IP camera. Moreover, the drawing area tells *who's online* (or *presence*), knowing continuously where the partner is looking and sketch-

ing. The two HIS were installed in two distant universities (UC. Berkeley, School of Architecture and the School of Industrial Design at the Université de Montréal) (Figure 1). This setting engaged all remote collaboration issues, such as multidisciplinary, differences in time, language and culture. Verbal exchanges were made possible by a commercial voice-over-IP system. This paper describes the HIS as used in the first steps of the Augmented Design Studio; see Dorta (2007) for the original HIS description.

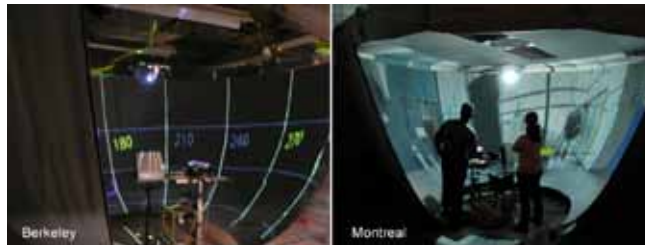


Figure 1. The first interconnected HIS, here with part of the spherical screen open

4. CI Loop

In order to measure the collaborative design, Kvan and Geo (2004) have proposed the use of design framing, as stated by Minsky's four-level frames: synthetic and narrative as *depicting* frames and semantic and thematic as *descriptive* ones, but aspects related to negotiation and moving during ideation are not considered. Previously developed, but improved further in this study, the CI Loop is a methodological compound instrument grounded in Bucciarelli's (1988) *design as social process*, Schön's (1983) *reflective conversation* and Goldschmidt's (1990) *graphical representation of concepts and actions*. The CI Loop is based on five elements common in the analysis of the design conversation and design process among those three authors: *naming*, *constraining*, *negotiating*, *decision making* and *moving*, with sub-elements for each one and their relationship with gestures (Dorta et al, 2010). Designers will be *naming* the object being discussed, *constraining* the project through its requirements and boundaries (time, budget and other constraints). The *negotiating* was, in this study, expanded to three subcategories: *proposing*, verbally making a design proposal, *explaining*, substantiating, and *questioning*, raising issues about or giving a rebuttal to a given proposal. *Making decisions* is specifically agreeing or disagreeing on a proposal, thus marking the end of the negotiation. *Moving* is adding to the representation and making pointing and sketching gestures. The first four actions are usually in the form of verbal exchange, while the moving is an act, which transforms the design situation (Goldschmidt, 1990).

We called this CI pattern a loop because it repeats itself, and it seems to spring from one to the next, often creating sequences of loops. A CI Loop (1) has to involve more than one participant; (2) starts with a naming; (3) ends with a decision-making (agreement or disagreement); (4) has to have an exchange, so at least one constraining, proposing, explaining or questioning (and a “dis”-agreement); and (5) has to have at least one occurrence of moving or proposing, or both.

5. Experiment

Two teams of two students, architecture (Berkeley - team a) and industrial design (Montreal - team b), participated in the ideation of a bus shelter as ad-hoc project for about 6 hours over 3 days in the following sequence: On the first day, after introduction and training, the 4 participants launched in a first ideation of 50 minutes. On the second day, Montreal worked in the HIS with a rough physical model for 38 minutes (time spent making the model outside the HIS is not accounted). Then the two Berkeley architects joined them for a 50-minute work session starting with the presentation of Montreal’s three design proposals, interspersed with discussions about relevant supporting concepts, leading to some co-design. The Montreal team retired, leaving Berkeley to continue for an 80-minute session. The last day, both teams worked together at all times. First Berkeley presented their work (60 minutes), and then they co-designed together to complete the concept (75 minutes). The teams had to work in a suggested timeframe, which was adapted to come to a natural stop at the transition times. The CI Loop was used to code all 6 hours of video recordings in 10-second increments, noting all actions occurring in each increment. If an action lasted longer than 10 seconds (e.g. a particularly long explanation) it has been accounted for multiple times, marking its importance in time.

6. Results

In this study, we have observed that there are 2 different types of CI Loops, (1 and 2), corresponding to the different lengths of loop observed in a previous study (Dorta et al, 2010). CI Loop 1 (Figure 2) focuses on securing larger design *concepts*, which invites wider verbal exchange (more negotiations than moving). CI Loop 2 focuses on giving *form* to the previously agreed general concepts and is involved with specific issues that can be resolved in and by the representation. These exchange are usually shorter, having less negotiations and more moving, since they are confined to a specific issue present in the representation.

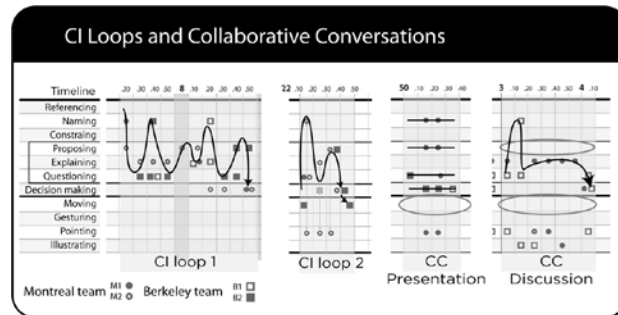


Figure 2: CI Loops (1 for **concepts** and 2 for the **form**) and CC (Presentation and Discussion)

6.1. COLLABORATIVE CONVERSATIONS

If only four out of five requirements of a CI Loop are met, the exchange was a Collaborative Conversation (CC) indirectly involved in the ideation. CCs, observed for the first time in this study, have a predictable pattern (Figure 2), but are neither a loop (no springing in the argumentation from one pattern to the next), nor do they directly move the design forward. They are either *presentations* of previously agreed design, or *discussions* about concepts indirectly related to the design. The two CCs share an absence of moving. *Presentations* have a lot of proposing, as speakers present and explain their proposals, without negotiations between participants. *Discussion* about indirectly related topics have much back and forth between explaining and questioning but no proposing or moving.

6.2. LENGTH OF EXCHANGES

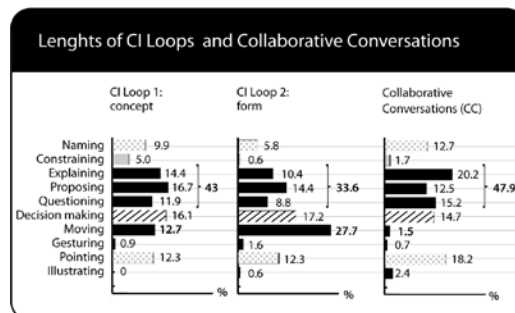


Figure 3: Time spent in collaborative exchanges

In CI Loop 1 more time is spent talking and deciding, then moving: 43% is devoted to the negotiation triad and 12.7% for moving (Figure 3). These loops average 68 seconds, whereas CI Loop 2 averages 24 seconds. In CI Loop 2, the time spent negotiating (explaining, proposing and questioning) was 33.6% versus 27.7% moving. This is almost one to one negotiating to moving, compared to CI Loop 1, where there are 3 negotiations for 1 moving. The CCs (all together) hold the most explaining and questioning of all, spending 47.9% in negotiation and only 1.5% moving. In CCs, *presenting* differs from *discussing* in that a lot of design proposals are stated when presenting and nearly none are when discussing a concept.

7. Conclusions

The interconnected HIS seems to support remote co-design and cooperation proving itself as a distributed computer-mediated CI system based on a hybrid place metaphor. Participants appear to have felt teleported in each other's representations, experiencing telepresence and understanding the project in spite of differences: in languages and accents (none of the participants were native English speakers); in professional culture (industrial design / architecture); in time zone; in seeing the other participant (locally) and not seeing them at a distance (which lead us to add a participants' video window, and consider more closely the importance of gesture in the design communication, as well as in the confident collaboration). Yet, in spite of the differences, we have seen in the last co-design session (last 75 min) many quiet drawing moments where collaboration happened across the distance: with participants in each location drawing together the same object in silence (very much in synch with each other); or with one participant from Montreal guiding a participant from Berkeley in his drawing.

The CI Loop, compared to Minsky's framing, shows in more detail the collaborative exchanges, although there is a general correspondence between CI Loop 1 and the high design descriptive frames, addressing problem and contexts, and CI Loop 2 and the depicting frames repeating instructions and creating scenarios from the design brief (Kvan and Gao, 2004). This study saw the first steps of the Augmented Design Studio with only two interconnected HIS (only 4 participants). We envision the Actual Design Studio as a network of HIS all interconnected symmetrically and asymmetrically (laptop and HIS) enhancing multidisciplinary Collaborative Ideation in professional and educational design studios. In a subsequent study (Lesage and Dorta, 2011), we compared the HIS to an Internet-based whiteboard software. Those results favour the HIS because of the immersive experience.

Acknowledgements

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INTERACTION IN TERMS OF INDIVIDUALITY AND INTELLIGIBILITY

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Abstract. This paper points out that “interaction” is not only a scientific issue but also a social-cultural issue. The relationship between the user experiences and the behaviours of the system should be emphasised. The “Individual-Intelligible” coordinate system is created to compare and evaluate the interactivity of various systems, it provides a new design space for researches or students experimenting with interactive systems. Four experiments are discussed with the new formulation of the interaction.

Keywords. Interaction; individual; intelligible.

1. Introduction

There is a great diversity of initiatives from architects, artists and students using new technologies to create their own kind of interactive systems, however, a common language for comparing, evaluating these systems is not dispensable. It is widely agreed that interaction is not equal to reaction and there is a feedback loop between the system and the user or the environment. Nevertheless, a wide-recognised formulation of interaction is still not available. To discuss the quality of “interaction”, this paper addresses the significance of individuality and intelligibility as the coordinates of the interactivity of the dynamic systems, especially for researches or students in (architectural) design areas.

The “Individual-Intelligible” coordinates concern about the social-cultural aspects of the systems: the individuality emphasises the machine should attract and involve the user into a meaningful conversation; the intelligibility allows the user to associate the behaviours of the system with its “goal” according to causality. Here, the relations between the user experience and

the system behaviours are highlighted. With the coordinates, various interactive systems can be compared and evaluated; furthermore, the interconnection between individuality and intelligibility defines a design space, providing a new perspective for the designers. To verify the Individual-Intelligible coordinates, four experiments have been completed and they are discussed in “Four experiments” section.

2. Interaction and isolation

What is interaction? In the domain of architecture or media design, it is acknowledged that the interaction is beyond reaction, however, there are few further researches on this topic though it is of great importance. Very roughly speaking, viewpoints on interaction lie in two main categories: cybernetics (functionalism) and biology (or sociology) motivated theories. This section reviews some of them very briefly and points out the “isolation” crux.

Cybernetic paradigm plays an important role in interaction design. One deep theory is about the design of the “Braintenberg Vehicles” (further discussion in “Four experiments” section), which reduce the error (according a predefined goal) through the feedback loop between the vehicle and its environment. It is a typical self-regulation system (also called first-order system) according to Dubberly (2009):

The self-regulation system has a goal; the goal defines a relationship between the system and its environment, which the system seeks to attain and maintain.

Comparing to the first-order system, the second-order system is a learning system which is able to modify the goals according to the effects of the action. While, the “Braintenberg Vehicles” theory suggests an intelligent model employing artificial neural networks to connect the sensory and the motor. Both theories try to build intelligence based on feedback loops, however, neither of them take user experience into account. The relevant approaches could prevent people to understand the machines, for the underlying mechanisms are too “professional” and too “sophisticated” beyond people’s everyday knowledge. Furthermore, the “goals” of these complicated systems may represent the “false needs” according to Marcuse (1964). In short, one-sided theories about improving the control in systems could lead to the isolation of the machine and the people.

On the other hand, more and more interaction designs adopt biology concepts e.g. adaptive and metabolism. Usually the “bionic” approaches take account of the social aspects of the systems and pursue meaningful conversations between the system and the users. For example, Daan Roosegaarde’s

interactive “bushes” create

An architecture of social relations invites the visitor to spontaneously perform and thereby construct alternative physical, architectural, urban and social meanings. (Bullivant, 2007)

For a successful conversation, creating “personality” is essential for these systems. However, if these systems have no well-defined goals to achieve and maintain, then people can’t understand them very well since these machines can only be perceived by feeling, not by reasoning. So these systems are reasonable enough.

3. Individuality and intelligibility

If interaction design can not improve the user’s understanding of the meanings and the possibilities of the communication between the user and the machine, this kind of interaction could lead to the isolation of them. Under this situation, the intelligibility of the system becomes crucial. To make itself comprehensive, the system has to manifest both its goal and the way it achieves the goal. In other words, intelligibility allows people to associate the behaviours of the system with its goal. The “goal” is a function in a narrow sense. In general, it relates to the equilibrium states of the dynamical system. In fact, the notion of intelligible is consistent with one of the ideas of modern architecture: the building should express its function and manifest the rationality of its being. Applying this principle in interaction design, the system should expose its mechanism to the users rather than encapsulate its functions.

Nevertheless, intelligibility is not enough for a robust interaction because it doesn’t guarantee a successful communication. At least, the system has to attract the user into to a conversation. In the words of Bullivant (2007), the machine needs “personality”. Wolfe (2010) even thinks about a form of “embodiment” to make the system alive. Generally, the interactive system needs to be individual, to achieve its goal via alternative or interesting behaviours. In terms of dynamics, an “individual” system makes unpredictable temporary movements following predictable attractors. Thus, interaction design is to explore unique and interesting “movement-attractor” relationships.

Intelligibility and individuality could represent a new coordinate system for the interactivity of dynamic systems. If a system can catch the user into a meaningful communication (individual dimension) and enable the user to associate its behaviours with its goal (intelligible dimension), then the system is able to support a healthy interaction.

Individual-Intelligible are not two independent dimensions in Cartesian system, they can be regarded as a pair of characteristics connected to each

other inherently. The Individual-Intelligible coordinates define a design space of interaction. Although there are no straight way towards high individuality and high intelligibility, here are some hints:

- Perform a task in alternative ways which are novel or interesting.
- Let the system expose its mechanism.
- “Invent” meaningful tasks for the system.

These strategies deal with interaction based on user experiences, with a social-cultural perspective rather than from a scientific background.

4. Four experiments

The motivations and the solutions of the four experiments are quite different, however, they show how Individual-Intelligible concept plays an important role in different projects.

The research commences with the “Braitenberg Vehicles”: If put a vehicle with two light sensors and two motors on the floor (Figure 1), how to make the vehicle move to the brightest location? The most difficult task for the vehicle is to “know” the brightest point, only by two light sensors each of which only outputs the light intensity in a particular direction. In fact it’s not necessary for the vehicle to know the brightest point, if its behaviour could produce the phenomenon of “moving to the brightest point”. Through this way the behaviour of the vehicle shows how it reaches the “goal” and makes itself intelligible. The experiment also implies that there are a lot of different types of behaviours which can fulfil the same task of “moving to the brightest point”. Such multiple choices on behaviours are essential for developing individual characteristic of the system.



Figure 1. An implementation of Braitenberg Vehicle.

The second experiment considers two opposite solutions for dynamic facade: one solution regards the facade as a media surface, but it doesn’t make much

sense for the inhabitants behind the facade. In contrast, other solution concentrates on the physical functions of the facade elements, without contributing to overall facade patterns. Actually it eliminates the individuality of the facade as a whole because all the elements work independently. So the experiment tries to integrate the display of patterns and the physical function (shading) into one system. Since shading requirements are usually locally distributed, they can be compatible with some global patterns. For example, a “wave” pattern can be constructed even if a considerable percentage of the facade elements are locally constrained by different users behind the facade (Figure 2); the amplitude and the wavelength are adapted to the constrained elements. By experiencing the facade from interior and exterior, an inhabitant can understand the system as follows: if someone regulates one element, the whole system can adjust its pattern to the change. The special mechanism by which the system maintains its pattern shapes the system’s individuality, which can be perceived by the users during interaction.

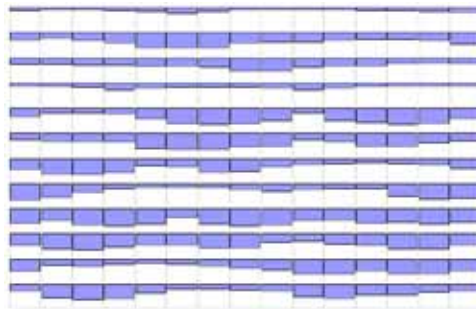


Figure 2. A “wave” pattern can be constructed though many elements are locally constrained.

In general the two approaches above are problem-solving oriented. There is another situation that the designers have to “invent” the behaviours of the system because there are no problems to solve or the problems can not be well defined. This situation has been studied deeply by Rittel (1973). During the present time, creating responsive visual and audio effects in space becomes popular, however, the interaction is weak if people don’t understand what the system is doing and subsequently they don’t react actively. The following two projects seek individuality and the intelligibility by inventing new behaviours.

The “avaGarden” project creates lighting and buzzing effects in interior space and relates their patterns to the “moods” of the space. Several nodes are built and distributed in one floor. Each node is equipped with sensors (light, temperature and sound sensors), output devices (LED and Buzzer) and wireless communication devices (XBee). These nodes construct a wire-

less network. The “mood” of an interior space is evaluated according to the data collected from the nodes. For instance, if the current data indicates one area of the floor is good for working, then the node in that area produces a special buzzing melody and blinks the LED with special intervals to indicate the “working” mood. The mapping from physical conditions to the moods relates to the activities of the simulated agents “living” with the real-time data collected in the floor (Figure 3). People also influence these virtual agents since the real-time data are related to the people’s activities in the floor. When people experience the transition of the moods and observe their counterparts in the virtual environment, they could understand the behaviours of the whole system and perceive the individual characteristics of the system through interaction.

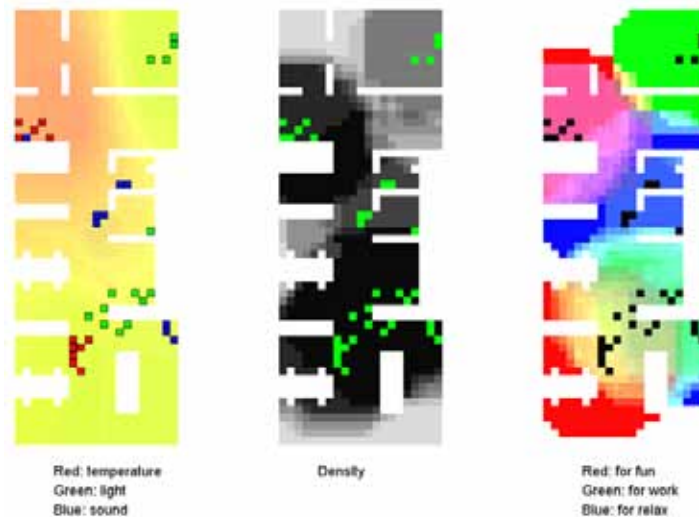


Figure 3. The visualised real-time data in one floor (left) and the moods of the space related to the activities of the virtual agents (right, the agents are represented by dots).

Last project develops a system learning the user’s body reaction to music. It’s very common that a person moves his body in response to a piece of music unconsciously or consciously. A device (the user can hold it as a baton) with two accelerometers is developed to catch the user’s hand motion. The relations between the music and the personal motion are classified (Figure 4) by a pattern recognition algorithm (Kohonen, 2001). After this learning period the user could make his personal music simply by waving his hand with the motion-catch device, for the motion can be mapped to sound immediately according to the learned motion-sound map. As a result, the device becomes a

musical instrument. It's important that this map is neither random nor universal, but very personal. This system builds its individuality based on the user's personal characteristics (personal reaction to music) which are encoded via a machine learning process. By playing with the instrument, the user can find it intelligible when he realises that the instrument is to imitate his own patterns.

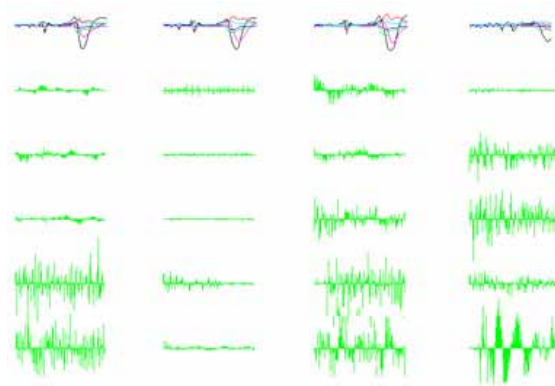


Figure 4. The classification of the motion-sound patterns (one typical motion is associated with several pieces of sound, only four of the typical motions are showed in this figure) for a personal motion-sound map.

5. Conclusions

Previous section illustrates several applications following the Individual-Intelligible formulation. It is clear that the two concepts – individuality and intelligibility are not additional requirements for interactive systems, but two intrinsic characteristics of the system which the designers always have to deal with. The Individual-Intelligible coordinate system could make the two interrelated characteristics explicit in design process.

It is always rewarding to explore the relation between the user experiences and the behaviours of the system, which can be regarded as the core of interaction especially in design areas. The new coordinate system provides a conceptual tool for designers to speculate, to evaluate and to develop this relationship towards more robust interactions.

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VIRTUAL AND INTERACTIVE ENVIRONMENTS III

28.	Two conceptual design tools and an immersive experience: Beyond the pragmatic-pleasurable split in UX <i>Annemarie Lesage and Tomás Dorta</i>	291
29.	Active buildings: What can we do about buildings that simply stand still? <i>Yasu Santo, John H. Frazer and Robin Drogemuller</i>	301
30.	Mirrored message wall: Bridging the real and virtual community <i>Beng-Kiang Tan and Jung-Ho Yeom</i>	311
31.	A study of variation of normal of polygons created by point cloud data for architectural renovation field <i>Tomohiro Fukuda, Kensuke Kitagawa and Nobuyoshi Yabuki</i>	321

TWO CONCEPTUAL DESIGN TOOLS AND AN IMMERSIVE EXPERIENCE

Beyond the pragmatic-pleasurable split in UX

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Abstract. In a recent study, we compared two conceptual design tools supporting collaboration, a whiteboard software accessed through Internet, and a hybrid immersive system, the Hybrid Ideation Space (HIS). The result of the study appeared to favour the HIS because of its immersive qualities. In this paper, we seek possible explanations as to why immersion delivered a better experience, by looking at the mental workload in relationship to the experience. For the workload we rely on Wickens' four-dimensional multiple resource model, specifically processing codes (verbal/spatial) and visual channels; and for the experience, Csikszentmihalyi's concept of flow and our own concept of Design Flow. The designers seemed to be responding to different styles of information processing required of them by each tool, one being more experiential and the other requiring a heavier mental workload. Insight in the cognitive underpinning of a strictly pragmatic immersive experience suggests that UX has also to do with how the information is received and processed by users, without isolating the functional from the rest of the experience.

Keywords. User experience; immersion; flow; mental workload; Hybrid Ideation Space.

1. Introduction

In a recent study on the impact of immersion on ideation (Dorta et al, 2011), we compared two conceptual design tools supporting collaboration, an immersive system and a non-immersive whiteboard application. The results favoured the immersive system as it delivered better performance. But why exactly did

immersion deliver better on ideation in this case? Furthermore, the *quality* of the participants' experience with each tool appeared to have been very different, although they said, in exit interview, they felt both tools worked "well". In this paper, we seek to provide an explanation for this difference in experience quality beyond stating that one tool is immersive and the other is not. We based our analysis on Wickens' (2002) four-dimensional multiple resource model, specifically the processing codes (verbal/spatial) and visual channels. We looked at the way information reached the participants and what channel they respond with in relation to their psychological experience as assessed with Csikzentmihalyi's (1988) concept of flow.

In this case study we compared a whiteboard application accessed through Internet (Vyew™), and a hybrid immersive system (the Hybrid Ideation Space or HIS) (Dorta, 2007). These were chosen because they both have intuitive interfaces supporting freehand sketching over real-life images or photographs. The study followed a team of two landscape architecture students, collaborating on the conceptual design of two slightly different ad-hoc landscape design projects. The study ran over two days, using Vyew on the first day, and the HIS on the second. During the protocol the experience was assessed using Csikzentmihalyi's (1988) concept of flow and the NASA TLX workload, while the recorded videos of the protocol were coded using a processing codes analysis grid we developed. The results show a noticeable difference in the balance between verbal and spatial processes involved in each experience, one being polarised toward verbal processes and the other being distributed between the two. We feel this approach can shed a new light on immersion in design tasks, and ultimately contribute another puzzle piece to the general understanding of what user experience (UX) is made of.

1.1 UX AND THE PRAGMATIC / PLEASURABLE SPLIT

In the past decade, much research has been done on UX, trying to observe it, define it and measure it. Although there is considerable receptivity towards the concept of UX, there is no consensus on a definition yet. Some models have more currency than others, such as a vision of the experience extending from a core pragmatic interaction into ever widening contexts of use (e.g. physical settings, technological, psychosocial, or cultural contexts) or Hassenzahl's (2007) hedonic/pragmatic model, which posits that within a single experience there are two sets of goals: the pragmatic goals, extrinsically motivated ("do-goals"), and the hedonic ones, intrinsically motivated (or "be-goals"). In either model, the pragmatic and pleasurable are seen as distinct and cumulative. But this split is not always clear in real life. In this particular case study there is positive subjective user experience as attested by the flow results, and

no divergent be-goals or added on contexts (due to the ad-hoc nature of the project) bearing on the experience of these participants. The positive user experience sprang from the pragmatic interaction and goals. Perhaps seeing the experience in layers (pragmatic or pleasurable) may not be the best way to approach UX, since it is far from clear that it is experienced in layers. Actually, optimal experiences are said to be holistic (Csikszentmihalyi, 1988) such as the concept of flow, an experience where the subject experiences a deep sense of control, altered sense of time, loss of self-consciousness, and a merging of action and awareness. Flow is holistic (not layered) and takes over our full attention.

1.2 THE FOUR-DIMENSIONAL MULTIPLE RESOURCE MODEL

Wickens' (2002) four-dimensional model was originally developed to avoid dire multitasking scenarios (such as may occur when driving in heavy traffic on unfamiliar roads while trying to activate a newly purchased GPS). Instead of using this model to improve the experience by reducing risks and issues, we are using it to analyse a full attention, non-critical situation, namely collaborative ideation.

Wickens distinguishes four distinct dichotomous dimensions that have an impact on time-sharing performance, associated with distinct physiological mechanisms. We will focus on the processing codes (verbal / spatial) and the visual channels. Processing codes define the distinction between verbal, linguistic, analytic, abstract on the one hand, and the spatial, analogical, concrete processes on the other. This verbal / spatial dichotomy apparently is responsible for the high degree of compatibility of the manual and vocal responses, the manual usually responding to visual, both spatial in nature, and vocal to auditory, both verbal. There are two visual channels: focal and ambient vision. Focal vision will operate as a verbal/abstract process if it narrowly focuses on fine detail and pattern recognition, and as a spatial process when the focus is wide and all encompassing. Ambient vision relates to peripheral vision, and is used for sensing orientation and motion. Collaborative ideation can be seen as leaning on the verbal processes since it is the act of collaboratively exteriorizing abstract mental images first through words then through visual representations.

1.3 IMMERSION

Boellstorff (2008, 112) defines it as a state of consciousness where “sensory experience of the actual world is sufficiently muted, and the sensory experience of the virtual world is sufficiently heightened, that persons felt they were no longer in the actual world”. This general definition relates to virtual reality as

found in 3D virtual worlds, but not to an augmented reality approach. In this study, the immersive experience was had no loss of awareness of the actual physical body, as the HIS is a life-size immersive system where the designers can move, gesture, physically turn around as they are surrounded by their conceptual representation. This kind of immersion is closely related to the sense of spatial presence, which is generally understood as “the subjective experience of being there” (Balakrishnan et al, 2007). In this case study, we understand this *subjective experience* as being the result of the psychological and the physical experience from interacting with the interface and virtual information as the designer is engaged in the ideation task.

2. Assessing processing codes and responses

We developed an analysis grid to capture the verbal / spatial processing codes and responses based on Wickens (2002) and on our observations of the collaborative ideation activity with each tool. The first category is visual processing, we note where they look: 1) *on the tablet PC*, narrow focus on detail and pattern (verbal processing); 2) *scoping the immersive representation*, (wide focal vision including some ambient vision, spatial processing); 3) *not looking at any representation*, usually looking at each other when discussing (mixed processing); 4) *staring reflectively at the representation*, this kind of absorption happened mostly in the HIS (wide focus with strong ambient vision, spatial processing). We noted the use of the pen tool: for drawing (spatial) or writing (verbal); the use of the body as tool when pointing with finger or laser pointer, or by gesturing with arms (both spatial). Lastly we also noted the body posture because it was strikingly different with either tool, as fluid and at ease (spatial), often accompanying less stressful states, or strained (taxing the process).

2.1 ASSESSING THE EXPERIENCE

To assess the experience, we use the concept of flow, which is a complex psychological state that describes a perceived optimal experience characterized by engagement in an activity with high involvement, concentration, enjoyment and intrinsic motivation. Flow state is determined by the balance between challenges and skills (Csikszentmihalyi and Larson 1987). The relation between perceived skills and challenges gives rise to eight possible dimensions (Massimini and Carli 1986): apathy, worry, anxiety, arousal, flow, control, boredom, and relaxation.

3. The experiment

3.1 TOOLS

Vyew is an Internet application for whiteboarding, supporting remote and local collaboration. It was accessed through a tablet PC with a 13" screen, shared by the two participants. They used plan view and elevations retrieved from Bing™, Google Maps™, and Google Street View™, which they used as background for their sketches.

The HIS (Figure 1) is a hybrid (analogue / digital) immersive system developed by the Hybridlab (Dorta 2007) allowing immersive, intuitive, freehand sketching on a tablet PC, and immersive physical model making, in real time and life-size. The designers stand inside their representations, which is projected on a 5m diameter semi-spherical screen surrounding them. It augments traditional tools (sketch and models) with digital capabilities. The HIS has been evaluated and compared (Dorta et al, 2009) and consistently appears to enhance collaborative ideation.



Figure 1. View inside the HIS as designers sketch over an immersive photograph

3.2 PROTOCOL

The comparison between Vyew and the HIS was done through the conceptual design of two different ad-hoc landscape design projects using the same site. The study ran over two days, using Vyew for 75 minutes on the first day, and the HIS for 49 minutes on the second. This discrepancy in time accounted for the fact that on the first day, they spent more time getting acquainted with the site, time that was an investment for both projects. On the first day, the partici-

pants went through two phases: a first one where they analysed the site from Internet map sites to identify all the variables and issues with the site regarding the given project; followed by an ideation phase where they came up with a few concepts. On the second day their work in the HIS went through three phases. First they worked from a rough physical model with enthusiasm until they realised their would-be concept was actually a dead-end; then they went through a stressful phase, accompanied by a short break down in communication as they looked for a way forward. The third phase was a good ideation session yielding a concept they were very pleased with. The participants were two 3rd year landscape architecture students used to working together.

3.3 DATA COLLECTION

Three types of data were collected: (1) workload, (2) experience and (3) cognitive processing codes and responses. The participants filled a NASA TLX workload questionnaire after each project. The experience was assessed using Csikzentmihalyi's (1988) concept of flow and Massimini and Carli (1988) 8 dimensions of the experience. Because assessing experience is a subjective exercise, we have resorted to ask the participants to review individually the videos of the each session with us and to identify their psychological states. The participants called out their psychological state more or less every 30 seconds, which we recorded on a data-sheet divided in 10-second increments. This is the best way we have found so far to measure the experience without interrupting it. Nevertheless, we are aware that not everyone would be a good participant for this type of data collection; luckily these were, although they were students. They had a keen understanding of the concept of flow and relevant other dimensions. The cognitive processing codes and responses were identified by applying the analysis grid to code the video recordings of the two sessions, making annotations for every 10-seconds increment.

4. Results

4.1 WORKLOAD

A typical workload will have matching performance and mental demand, which is the case for Vyew (Figure 2); but in the HIS the mental demand is very low while the performance is very high. Temporal demand was higher in the HIS as the participants felt pressed by time (they had less time than with Vyew), which lead to a greater effort.

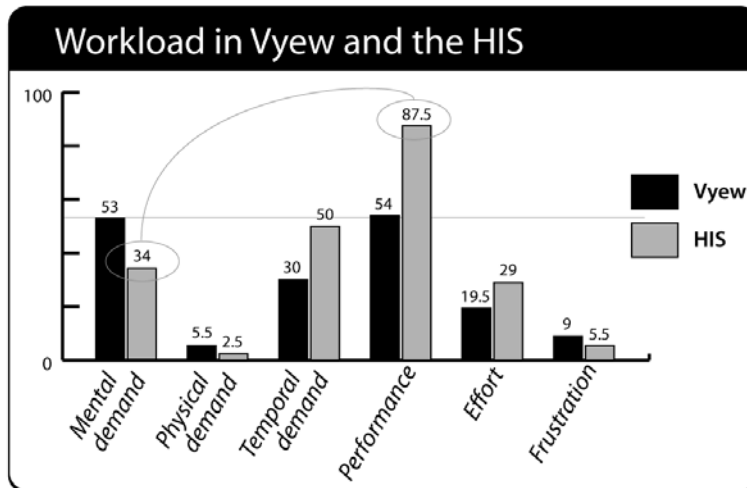


Figure 2. Workload for the two tools

4.2 THE EXPERIENCE

The experience with Vview (Figure 3, top left graph) is marked by a large band of alert state running throughout this project. The participants said they were in flow a number of times, particularly in the second phase (ideation) but these episodes were short. The experience in the HIS (Figure 3, top right graph) did not have this constant alert mixed in with every other state and it shows a strong, unmitigated flow at the end.

4.3 PROCESSING CODES AND RESPONSES

In Figure 3 the results of the assessment of verbal processing codes and responses are shown in a black line and the spatial processing codes and responses are in grey volumes. On the whole, the HIS called for more spatial processing, especially during the strong flow phase.

In Vview, the visual processing (Figure 3, graph A Vview) was dominated by a complete focus on the tablet PC. The participants did not have a wider representation to look at from time to time, but they did look up at each other, away from any visual representation (Figure 3, graph B Vview), to discuss their ideas. This allowed for wider focal and ambient vision (spatial processing). They made most use of this in the peak of the flow zone. Perhaps this released some mental workload associated to the continuous narrow focus (analytic/verbal processing) on the tablet PC. Doing so meant getting away from the visual representation and relying on words, abstract mental images

(linguistic/verbal processing) and gestures (spatial processing; Figure 3, graph D Vyew) to continue the reflective conversation. Graph C (Figure 3) shows and even use of the pen tool for drawing (spatial), as well as for writing (verbal). The two participants have shown signs of discomfort and straining as they sat in front of the tablet PC (holding their back, crouching over the tablet PC to see better, etc), which have put a strain on them. Towards the end of the session, when they started looking up and using arm gestures, their body posture showed signs of ease and fluidity.

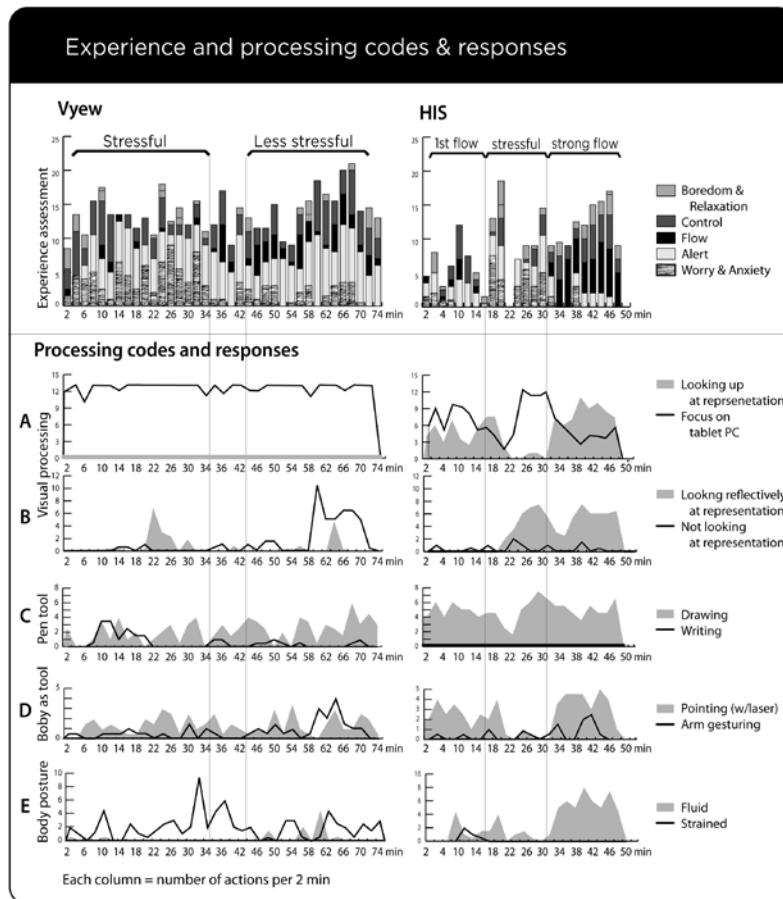


Figure 3. Comparative view of the five cognitive markers of processing codes as they correspond to the experience

In short, Vyew has supported some spatial processes (drawing, indirectly supporting communicating through gestures) and a number of verbal, linguistic, analytical processes (requiring narrow focus on the interface; encouraging

note taking; when participants seek a wider focal vision, they had to let go of the visual representation and communicate through words; being a virtual Internet interface, it had no consideration for the involvement of the body, dissociating the body from the collaborative activities).

The visual processing in the HIS is mixed, moving from a narrow focus on the tablet PC to a wider one with ambient vision when looking at the immersive representation. The focus on the tablet PC seems to parallel the state of alertness in Vyew, and alert, worry and anxiety in the HIS (Figure 3, Graph A). Perhaps the narrow focus (and analytic processing) is best suited to respond to the inherent tension of the state of alert. In the HIS, the participants have looked up and scoped the immersive representation during episodes of flow (Figure 3, graph A HIS). The HIS offered mixed visual channels serving both verbal and spatial processes, in two representations, one on the tablet PC and one on the immersive screen. In the last phase of the project (Figure 3, Graph B HIS), the participants have enjoyed standing in the middle of the HIS, taking in the immersive representation before making a new proposal. The HIS appears to encourage reflective assessment leading to new proposals during flow episodes. This is related to the fluid body posture (Figure 3, Graph E HIS) and increase in laser pointing and arm gestures to describe a design (Figure 3, Graph D HIS). The body being in the same scale as the immersive representation can thus serve to express ideas physically.

4.4 DISCUSSION

There seems to be a parallel between the focus on the tablet PC and the pattern of alertness and stressful states experienced in both tools. In the HIS, where participants had a choice between focusing on the PC or having a more spatial focus on the immersive representation, they gravitated towards the PC when they were in a stressful phase. Apparently the narrow focus responded to their need to get in control of the ideation process. But once the ideas were acceptable again, they switched to the wider spatial focus to push those ideas to their full expression, thus experiencing the strongest flow episode of the two days (low stress with a fair amount of control and relaxation). In these moments it seemed as if the HIS interface in fact extended the ideation while still stimulating it anew again. These episodes had an autotelic quality to them (were self-propelled; contained their own goal and satisfaction). With Vyew, the progression from beginning to end has been even, but the quality of the final flow was mitigated by an equal amount of tension (alert) and stress (worry and anxiety) versus the less stressful states (flow, control and relaxation). It is not clear if this is particular to this project or if it is due to a mental overload brought on by the continuous use of a tool requiring mostly verbal/linguistic/

analytic processing to do a conceptual task. It is as if the narrow focus, verbal processor was a workhorse capable of the early heavy lifting in the ideation process, and the spatial processor were the fourth and fifth gears capable of stealth and great performance, with lighter workload. This could explain why, when using Vyew, the team felt the need to discuss their ideas away from the tablet PC once engaged in the flow.

7. Conclusion

What the immersive system permits in this case study is to complement an activity relying heavily on analytical, linguistic and verbal process, collaborative conceptual design, with an interface calling for mostly spatial processes. Not only do the two types of process do not burden each other, they might stimulate each other, leaving the designer with more than enough mental workload to deliver a good ideation. Instead of doubling the efficiency by multitasking, smartly putting to work both processing codes may be setting up the conditions for potential optimal experiences, whether we are following a pragmatic or pleasurable motivation.

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ACTIVE BUILDINGS

What can we do about buildings that simply stand still?

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Abstract. This paper presents background of our research and result of our pilot study to find methods for convincing building users to become active building participants. We speculate this is possible by allowing and motivating users to customise and manage their own built environments. The ultimate aim of this research is to develop open, flexible and adaptive systems that bring awareness to building users to the extent they recognise spaces are for them to change rather than accept spaces are fixed and they are the ones to adapt. We argue this is possible if the architectural hardware is designed to adapt to begin with and more importantly if there are appropriate user interfaces that are designed to work with the hardware. A series of simple prototypes were made to study possibilities through making, installing and experiencing them. Ideas discussed during making and experiencing of prototypes were evaluated to generate further ideas. This method was very useful to speculate unexplored and unknown issues with respect to developing user interfaces for active buildings.

Keywords. Interaction; interface; Building Information; participatory; adaptive.

1. Introduction

A building typically is a result of one-off project. Many buildings are designed from scratch and are never to be repeated. Most buildings are version-one unlike consumer products such as mobile phones and cars, which continue to evolve and be reintroduced with improvements with advantages clearly stated. Most building proposals do not even envisage how users can upgrade

or customise their spaces. Conventional project proposals simply do not assume buildings evolve with their users. While some architectural projects invite future users to participate in the design process, the resulting buildings often are frozen entities that simply stand still and do not adapt well to changing user needs. Our research began by asking how people can continue to fully and actively utilise their buildings.

Building Information Modelling (BIM) provides interesting possibilities for designing and managing buildings through effective visualisation and management of various building information. The current focus of BIM, however, is intended for architectural and construction industries. There are exceptions with which BIM is used for facility managements (CRC for Construction Innovation, 2007) but it is rare. Beside them, there is no evidence that a formal study was conducted to make BIM available for users. When manufacturing technologies make it possible for virtually anyone to design and produce one-off components, the limitation is imposed by buildings that are not designed to provide a framework to allow users to do it. If building information is used effectively in conjunction with open, flexible and adaptable building hardware and software, buildings will begin to offer different scenarios to how we utilise them to live and work.

We hypothesise that the missing link between the building information model and adaptive building systems is a set of interfaces for users to access, understand and utilise building information effectively and another set to customise their spaces easily. This paper aims to demonstrate how users can take participatory roles as agents of change through digitally enhanced tangible interfaces. We argue architects can take a new role to provide built environments for users to effectively instigate changes. Our future scope is to propose a strategy to design building systems that inform, encourage and motivate people to change their environments and improve the operation of not only one building but also a city as a whole through their participation. The purpose of this paper is to report how we began to do this.

2. Background

Technological solutions that deal with such as climate, hygiene and lighting have made significant advancement. It is surprising, however, that introduction of devices such as smart phones and laptops instigated significant changes to our lifestyles in the last fifteen years while our perception of what buildings do to support our lifestyles hardly changed since the industrial revolution. Kaspori extends this argument by stating that architecture is reduced to mere scenery for a world on the move (2005). To consider alternative scenarios for architectural possibilities, the aim of this research is to study how people can

actively use and interact with their buildings. Our main question is to ask what happens to buildings when the benefit of digital technologies to our lifestyle is pursued for designing buildings.

Since Sterling called networked object a Spime (2005), people began to recognise the importance of the Internet of things by experiencing more products, other than mobile phones and computers that exist within and influenced by the flow of information. The flow however is yet to influence much of the way buildings exist and how they are used today. As observed by some architects and critics (Kieran et al, 2004; Pawley, 1990) building users have hardly benefited from decades of technological advancements we have been experiencing through other products in our everyday lives. With respect to how a building serves its users, the expectation of what buildings do to support their users has not evolved much for centuries. As of today in the 21st century, our buildings still stand still.

This is not to say they all do. This research is influenced by Habraken's approach to design support structures and infill components to provide flexible building (Habraken, 1972). The method and scenario he proposed was feasible and practicality of his idea was clearly demonstrated with NEXT21, a residential building constructed in Osaka, Japan in 1993 (Figure 1). The building is composed of support structure and infill components, and spaces are rearranged periodically when demand of users changes. Its success however was mainly due to full-time researchers conducting workshop and consultations for its residents. Their contribution is significant to maintain the building and it is difficult to believe the building will continue to function successfully and as intended if the operation and maintenance were left solely to residents. This hints that hardware such as support structure and infill components is not enough to keep a building alive. Support systems and user interfaces are vital to keep adaptive buildings to be fully utilised.



Figure 1: NEXT21

Price's Fun Palace is one of the most flexible technologically mediated buildings ever designed. It is questionable, however, that it was capable of accu-

rately processing amount of building information and user instructions, interpret user intentions and respond to user needs. Moreover, it is hard to believe that, in the age when the idea of human computer interaction hardly existed, it offered sufficient interfaces for users to be able to communicate their intentions effectively to control complex array of flexible building systems. We argue that this is the main reason why a building like the Fun Palace has never come to exist as of today. Wigley describes “architectural responsibility to house humanity became a responsibility to shape flows of information” (2007). We need user interfaces to manage and utilise flows of information in adaptive and participatory buildings.

3. Research method and approach

This research is an “interpretive” research. Swann (2002) describes that interpretive research is “a form of qualitative research which is better suited to the behavior and sensitivities of human beings, relying more often on insight for the interpretation of human actions”. We conducted our research by constructing a series of prototypes, observing how people, including ourselves, use them and by understanding advantages and disadvantages of prototypes and context they were in.

This method was chosen because it is difficult, if not impossible, to find an adaptive building with real users in which we can test our prototypes. A building for users to customise simply does not exist. In order to pursue the idea of designing Active Buildings, we chose to begin testing a wide range of interfaces in isolation within certain relevant contexts.

Practical benefits of prototypes in our chosen contexts were not very important for this research because our aim was not to resolve specific problems in contexts we tested our prototypes. Our focus instead was to construct and test interfaces as proof of concept to identify possibilities of how users can interact with buildings and benefits of abilities to interact, and identify certain scenarios for Active Buildings.

4. User interface prototypes

We developed prototypes to study how building users can speculate, manipulate and learn actively or passively to influence the way a building works or is used. Our initial aim was to identify types of interactions between a building and its users and how certain interfaces allow this to happen. We identified from this study that there are several means for users to communicate and respond with building systems, as shown in Table 1.

Table 1. User participation matrix

	Active	Passive
Speculation	Investigation	Awareness
Manipulation	Conscious Selection	Automatic Selection
Learning	Participation	Observation

4.1 ANSI GRID AND MODULES

Australian National Sustainability Initiative (ANSI) is developing architectural systems to construct a lightweight, demountable space frame structure that supports a ‘green space wall’ (ANSI, n.d.). The key issue for developing a flexible and demountable architectural system is to understand possibilities of what the system is capable of offering. We recognised we need a tool to understand a variation of different spaces a set of building modules is capable of producing. We laser-cut a simple set of modular pieces and baseboard with triangular grid so that we could arrange modular pieces to study possible design options (Figure 2). Although the model is simple, it provided enough versatility to quickly and interactively study and recognise benefits of different spatial options collaboratively. This helped us to visualise one variation of how our modular components can be arranged to provide a building as shown in Figure 3.



Figure 2. ANSI building kits; Figure 3. ANSI building proposal;

Figure 4. Universal Constructor

This method involved extensive manual labour. It naturally led us to imagine how it can be streamlined with the aid of computer technology. For example, each piece can be augmented with sensors and actuators to inform users not only about arrangement of spaces but also about environmental, social and financial implications of combining and rearranging pieces. Each physical piece can be linked directly to a virtual component so that assembling modules create and alter information in BIM. The origin of this method can be traced back to Self-builder design kit developed by Frazer for Walter Segal for helping self-builders to design their own buildings (Frazer, 1995). Our idea is

to take this further and allow building users to redevelop and modify their own building after its completion with every associating data collected as building information models. Although linking BIM to tangible user interfaces is the ultimate aid, our initial research aim is to develop a system that allows and encourages users to engage actively to manage their building to the extent post occupancy evaluations become redundant.

4.2 UNIVERSAL CONSTRUCTORS

To study interfaces that support active user participation, our first approach was to utilise Universal Constructor (UC) Cubes developed by Frazer and AA Diploma 11 students in 1990 (Figure 4). Although the output of each cube is limited to 8 LEDs, there are about 100 cubes in working order and they provided a starting point to study user interfaces for reconfigurable smart modular systems.

Because the original baseboard for UC was damaged, we produced a new means to control UC cubes and connect them to a computer. This was achieved by a combination of laser-cut bases each of which can carry a column of UC cubes and controlled by Arduino microcontroller board (www.arduino.cc). We produced two bases for two columns of UC cubes, but the number can be increased infinitely in theory in a very flexible manner; they can exist in a group in a grid-like order as they originally were designed for, loosely as a group of individual interfaces, or even remotely across the Internet.

We found a set of scenarios can be developed to explain different use-case for interfaces such as UC cubes by going through all combinations of user participation modes in Table 1. For example, ANSI kit is an example of an active interface and can be used to speculate, manipulate and learn. The current form of ANSI kit, however, is too primitive to effectively provide information and feedback to building users because it relies too heavily on user experience and knowledge for the interpretation of consequences of changes. Further development of ANSI kit is to provide the rest of active participatory methods when it is augmented with digital technologies.

We envisage that users can also participate passively by not directly or consciously interacting with interfaces by making the systems to automatically and intelligently sense and interpret their behaviour. This has been researched heavily in building and home automation studies, for example, by Mozer (1999). Although it is a very important study for the successful deployment of active buildings, this paper will not discuss this because we are more interested in discussing user participation.

4.3 WINDOW SHADE CONTROLLER

To study and demonstrate basic principles of how active participation of building users can be encouraged and managed by tangible interfaces, we developed a range of simple means to actively and passively control venetian blinds in our office windows. The interface is consisted of UC cubes, motorised mechanism to turn the knob of venetian blind, light sensor, digital compass and accelerometer (Figure 5). Arduino is used to control all devices and communicate with a computer running a Processing application (www.processing.org) to upload data to Pachube (www.pachube.com) for sharing data with other networked devices.

Our experiment was to control the venetian blind by interacting directly with the interface, or control or monitor passively (automate) by detecting sunlight with or without a user interaction. The intention of this experiment was not to make a practical and useful set of interfaces but to study combinations of possible user-interface scenarios as mentioned earlier. It is more suitable to call this an artistic endeavour to identify possible architectural scenarios.

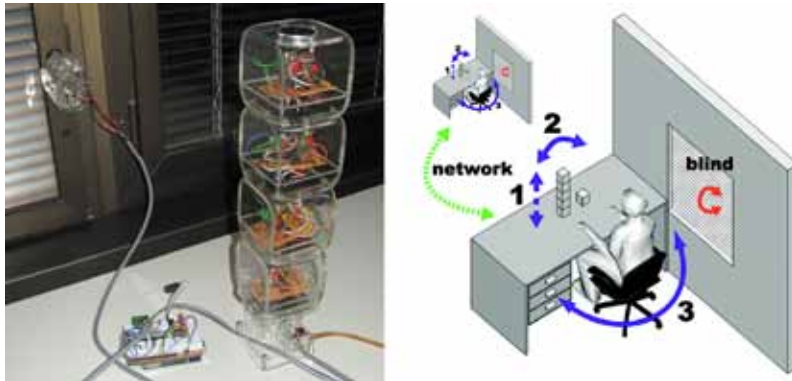


Figure 5. Shade Controller; Figure 6. Shade Controller Interfaces

All devices are connected and Arduino is programmed in such a way that there are three possible methods to control the venetian blind as shown in Figure 6. The method (1) is by stacking UC cubes, (2) is by tilting a UC cube column, and (3) is by swinging the chair. UC cubes visualises the intensity of light they receive by turning corresponding number of LEDs.

The method (1) allows users to set venetian blinds to a predetermined angle. Control device is programmed to rotate them to one extreme when five cubes are stacked on the base, another extreme when no cube is on the base, and other in-between positions are set when one to four cubes are stacked. The method (2) enables users to assign a specific angle to each number of stacked

cubes. Venetian Blinds rotate in one direction when the cube column is tilted to one side by reading accelerometer value, and the direction is reversed when tilted to another side, and the angle is stored when it is in an upright position. The third method triggers the rotation when the chair is swang, allowing a human behaviour to override the predefined position. The device is programmed to open the blinds when the chair is swung towards the window. They move back to the original predefined position when the chair returns to the original angle. A digital compass is used to measures the orientation of the chair.

These interfaces allow users to interact with blinds in several ways. Stacking allows users to set blinds to let the light come through with predefined intensities. Blinds rotate to maintain a chosen intensity as the light condition changes outside. When users require to fine-tune, they can interactively choose the right intensity for each occasions and store them to each number of cubes. Lastly, to allow users to rotate venetian blinds spontaneously, swinging chairs towards a window allow users to open them. This is meant to introduce a response to an intuitive action users take to look at the window. Blinds open so that users can look through them.

5. Discussion

The venetian blind experiment was conducted to learn how buildings could be activated for their users and identify a level of control they have to change their environment. The task was to identify something we can augment (venetian blinds), build tangible interfaces (UC cubes) and utilise control and feedback systems (Arduino and Pachube), to identify limitations and possibilities of building systems and user interfaces. The act of making them, discussion that took place during installations, further discussions we had through interacting with the shade controller interfaces were valuable.

Components we can retrofit to convert most existing buildings into Active Buildings are very limited. For example, it is hard to imagine a shade controller to become a product to be retrofitted because this would only be possible if window shading systems in many buildings were standardised. If however we can assume that all future building components are modular and will have open building information available to users so that they can be rapidly manufactured or purchased, number of scenarios we can develop for Active Buildings increases exponentially. We, as academics, tend to complain that buildings designed by students with Revit all look similar and boring. This is largely because components available in Revit and ability for students to utilise them effectively is limited. Similarly, if a building is designed to be active but users hardly understand the range of available options, it is easy to

imagine that the building will remain inactive and boring. We argue that BIM capable CAD packages are more than capable of managing required information, but means to access them for users is very limited.

When building users are informed and capable of making decisions, their building will no longer simply stand still. Building simulation interfaces like ANSI kit augmented with digital technologies can invite and encourage users to discuss current condition and future possibility of their building. Interactive interfaces not very dissimilar to Shade Controller can provide real-time feedback and collect user information for the collective benefit of building community. Users thus will activate buildings and their buildings will become active elements of their everyday lives.

This is very likely to change the way we operate as architects. What is at issue is participation as McCullough discussed (2004), and Active Building scenarios will demand architects to provide means for users to participate and allow them to become instigators of change. It will become an important role of architects to determine how building user community learns, which is an interesting response to criticism made by Brand about modern architectural practices (1997). It is also important to recognise that the design is not finite at the point of delivery (Kronenburg, 2007). This is very similar to how smart phones are purchased with basic configuration and users are expected to customise it to their liking. Backend supports to manage and utilise building and user generated data are being discussed (Fuller et al, 2008) and implemented (www.pachube.com). Infrastructure is already available and it is up to us to design the remaining missing links. Buildings can become co-adaptive (Santo et al, 2010) when it is designed and implemented.

It is also expected that architects, as the expert in the field, provide initial conditions that are set as a good starting point for all users. It is also expected that architects will continue to provide consultations to help users find good solutions during the entire lifespan of buildings.

6. Conclusion

We argue that the most crucial but overlooked issue architects are expected to understand for designing open, flexible and adaptive buildings is interfaces for building users. Through developments of simple user interfaces to design and use a chosen component of building systems, we identify it is important to introduce means for users to speculate, manipulate and learn, and ultimately participate, to allow users to activate adaptive buildings. Our research interests currently overlaps more with researches conducted in the field of Human Computer Interaction, which can be seen in the researches for example by Ishii (Ishii et al, 1997) and Dourish (2001). There is large volume of research

conducted within architectural discipline to prepare architectural hardware to work for open, flexible and adaptive scenarios, but architectural software is hardly developed to utilise them appropriately. Although our research is still in its infancy, we recognise it is slowly advancing to fill this gap to activate buildings for their users.

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MIRRORED MESSAGE WALL: BRIDGING THE REAL AND VIRTUAL COMMUNITY

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Abstract. The Mirrored Message Wall is a cross-world digital public display located in both real and virtual world, for collective sharing of thoughts and messages and serves to connect the real world and virtual communities. The wall was installed at a university library foyer and concurrently at a 3D virtual campus for user studies. This paper presents its design, social factors considered in the design, implementation, and the findings of the user survey and observations. The results confirm that such an installation does encourage people to interact with each other and the results will inform a better design for the next version.

Keywords. Virtual environment; second life; interactive message wall; public display; social interaction.

1. Introduction

In present day, communication within communities are both face-to-face and in virtual platforms. 3D virtual world platforms such as Second Life (SL) allow users to create their own world in rich graphical environment, create 3D virtual objects programmed to perform actions and to communicate with others through their avatars (Crowther and Cox, 2009). Many in-world communities are created for collaborating, sharing information, and doing online business. Many universities also build virtual campus and offer lectures in virtual classrooms ("Education in Second Life", 2010; Ritzema and Harris, 2008; Callaghan et al, 2009). Numerous communities are also setup in-world for groups of users who have the same interest, culture, or belonging. However their interaction exists only in the virtual world with other virtual users and is disconnected from the real world.

In the real world, in spite of pervasive use of the internet, some

people within communities still depend on public display for information and communication as not everyone is internet savvy. It is not uncommon to see announcements, advertisements and news on both physical and digital bulletin boards in places such as universities, subways, apartments and shopping centres. The digital public displays are usually minimally interactive (Churchill et al, (2004)) and one-way dissemination of information by manager to passers-by (Peltonen et al, (2007)). However, they have the potential for promoting the sharing of community content and public participation.

There are many projects that experimented with public displays of digital messages, images or videos. In Joe Blogg (Martin et al, 2006), users send messages and images using mobile phones onto a public display. In Tex-Tales (Ananny, 2004), users send SMS text message captions to a large scale photographic installation. In CityWall (Peltonen, 2007) users send media content using mobile devices to a large public display. Blog wall (Cheok, 2008) displays poems on a screen based on users' SMS. However, none of these projects deal with the connection between the virtual and the real space.

This research is interested in using public display as a means to connect physical and virtual communities and promote participation and sharing. The design method is a "tinkering" iterative process starting with sketching, low-tech prototyping, user survey and observations and repeating the process again for refinement of design. In our previous work (Tan, 2010; Yeom, 2010) we proposed a mock-up of an interactive message wall and did initial user study to guide the development of the design. In this paper, we implemented a prototype of the Mirrored Message Wall, a public display for large group users, located in both physical and virtual public space. The physical version was located in a busy part of our campus library, and the virtual version in our university's virtual campus in Second Life (SL). User observations and surveys were done to identify and verify issues.

2. Mirrored message wall - features and design rationale

The Mirrored Message Wall exists in both physical public space and virtual space and is a bridge to connect users of the real and virtual worlds. With a blend of real and virtual, it collects the hidden thoughts of passers-by and virtual users and allows everyone to see the collective aspirations. It consists of three components namely the physical message wall, the virtual message wall and message wall database (DB) API server (figure 1).

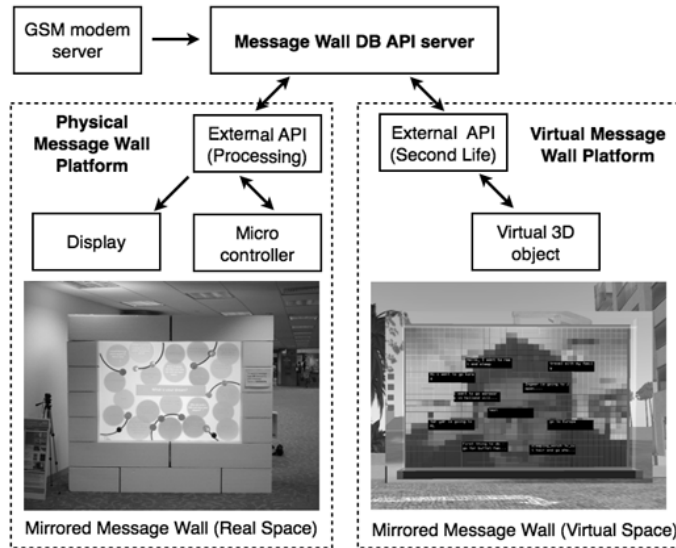


Figure 1. Message Wall in physical space (left) and virtual message wall (right).

The physical message wall consists of a rear projection system that is connected to a computer that in turn is linked by network to the DB API server.

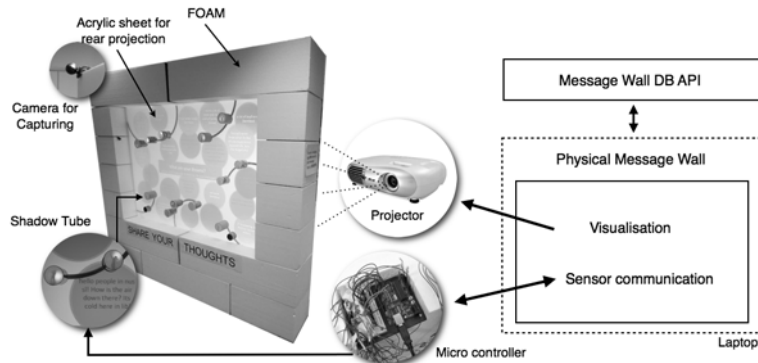


Figure 2. The Physical Message Wall Platform.

2.1 SOCIAL FACTOR - PRIVACY

In a community, awareness of other members may motivate participation of the community (Singer et al, 1999). So some public display projects for small groups share their status, image or movie clip (Greeberg and Rounding, 2001; McCarthy et al, 2001; Karahalios and Dobson, 2005) to indicate their

presence. However, for physical public discussion space located in a large common area, their shared information must take into consideration some social issues. For example, privacy is not an issue in a sharing process among members of a small group but in a large group, members are usually reluctant to open up and speak up their minds. This is because of their sudden enhanced sense of privacy. In the many research surveyed, most users are concerned about their privacy when online (Cranor et al, 1999; Rivera, 2004; Truow, 2003; Woo, 2006). We also found in our initial user observation (Tan, 2010) that most participants did not want to share their picture, movie clip, or voice with the public.

2.2. SHARING THOUGHTS AND MESSAGES - ANONYMITY

With the above in mind, the key consideration was to allow anonymous posting of messages for onsite users. By doing so we hope it can encourage more participation. In Second Life, the true identities of the avatars are not known so anonymity is guaranteed.

Messages can be posted using a mobile phone when a person stands in front of the physical message board, i.e. onsite users. Inside our university's Second Life Campus (virtual campus), users in their avatar personas (i.e. in-world users) can post messages by typing a message on the keyboard and posting it onto the message wall in the virtual world. Messages will appear real-time anonymously in both walls. To collect onsite users' messages, we use Short Message Service (SMS). When the (GSM) modem receives new SMS messages from the user at the physical message wall, it is sent to the Message Wall Server. Both Mirrored Message Walls in real and virtual space will display the message anonymously whenever a new message is detected. Displayed messages posted from the real world or virtual world are differentiated by different colour background. The messages posted from virtual world have blue background and those posted in front of the physical wall have yellow background. The message wall server saves messages and data from sensors and camera.

2.3 AWARENESS OF PRESENCE – ABSTRACTION, PRIVACY

To create awareness of presence, an abstract rather than a realism approach is taken. The reason is to safeguard privacy and also to maintain the anonymity in order to encourage more participation. The way it works is that a camera captures an image of people standing in front of the physical message wall and the image is pixelated and displayed as background on the virtual message wall indicating the presence of people at the real world message wall.

Silhouettes of human cut-outs in lighted shadow tubes indicate the presence of virtual users. When a virtual user (an avatar) is near the virtual message wall, a LED will be turned on showing a silhouette. The number of silhouettes on the physical message wall indicates crowd size in front of the virtual message wall.



Figure 3. Representing presence -- Pixelated Image Wall (a) and Shadow tubes (b)

3. Survey and observation findings of user study

The prototype model of Message Wall was exhibited at the campus Central library for user study for four days. The topic question was “What is your Dream?”. Over 100 messages were posted on the wall from real and virtual space and 47 users participated in a questionnaire survey. Some participants were also interviewed. To observe users’ interaction, their activities were captured with video camera. User created contents (SMS message) from the Message Wall DB API were analysed. This paper presents only the findings of survey from onsite users.



Figure 4. User observation with prototype model in the central library.

3.1. PRIVACY

In question 12 (*“Are you willing to share your pixelated image with the public?”*) of the questionnaire, we asked user’s willingness to share their pixelated image with public. 90% of the participants are willing to share their pixelated image while in our initial user study (Tan, 2010) only 6% of participants were willing to share their photos with the public (Fig. 5). So, if their image is pixelated, they are more willing to share with the public. It is important to extend participants’ range for sharing information to collect their rich created contents.

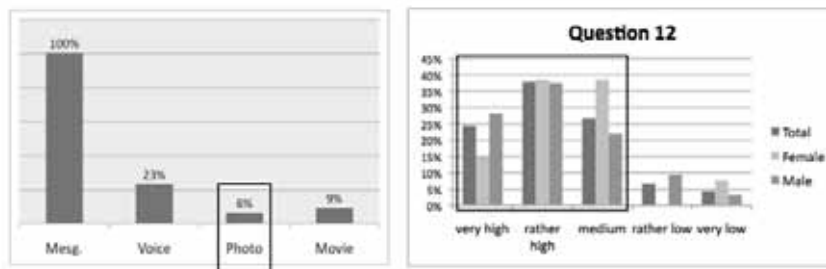


Figure 5. Willingness to share their photo in the initial user study (Left) and willingness to share pixelated image in this study (Right).

3.2. AWARENESS OF PRESENCE – ABSTRACTION

For question 11, (*“Shadows on the wall show the presence of virtual avatars, does it help you sense their presence?”*) of the questionnaire, only 47% gave a score of high and rather high (mean ranking of 3.17) (Fig. 6). Some users did

not understand what the shadows mean until it was explained to them. On the other hand, some users who have used our Second Life Campus understood it and found the idea of abstract representation interesting. More work is needed to understand what kind of abstract representation will be more engaging.

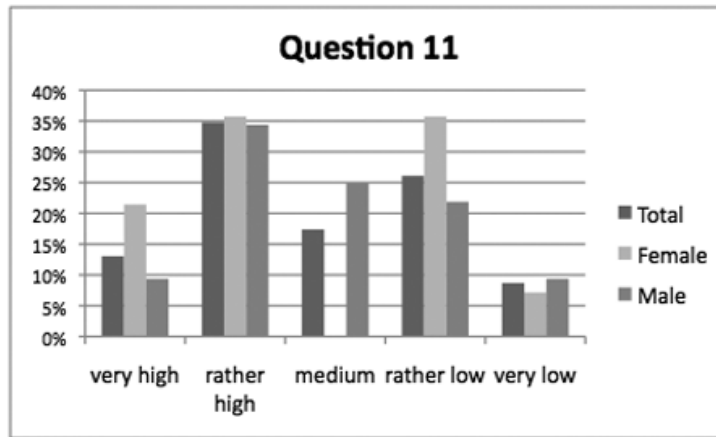


Figure 6. Result of (Shadow tube) Sense of presence question .

3.3 INTERACTION BETWEEN REAL AND VIRTUAL

An unexpected finding is that some avatar users from SL campus tried to communicate with the people at the physical message wall and vice versa. Even though the topic is “*What is your Dream?*”, an avatar posted “*Who is down there at the physical wall?*”. A user at the library posted “*Hello people in SL, how is the air down there? It’s cold here in the library!*”. It is interesting that people try to communicate with someone who is in another world even though they do not know each other. Local SL users posted messages mainly late at night or after midnight while the messages posted in the library were restricted to library opening hours.

3.4. ENCOURAGING USER COMMUNICATION

From the field observation and video observation, many users were interested to read others’ posted messages on the wall. When a user is accompanied by friends, they talk about the messages [Figure 7]. The displayed messages become a catalyst to start a conversation. This action was also found in the virtual community -- once they are in front of the message wall, some avatars tried to “talk” (text chat) about the messages on the wall.

3.5 MEMORY AND MAKING A MARK

There were two unexpected actions. Firstly, a number of users took photos of the messages they posted, for memory sake. They seem to get a satisfaction from externalising their thoughts, have it publicly displayed for all to see and wish to capture it for keepsake. Secondly, some people ignored the topic and posted birthday wishes and love declarations instead. These users treated the message wall as a space to vent whatever is on their mind with free expressions e.g. *“Thesis is killing me!”*, *“Happy Birthday to Pearl!”*.



Figure 7. Messages trigger conversations. Taking a photo of message on the wall for memory sake.

3.5 PROBLEMS WITH DESIGN

From user feedbacks and our own observations, we identified some problems of the Mirrored Message Wall. The visual design of the Message Wall can be improved to attract people. The graphic bubble on the screen is static and it takes too long (20 seconds) to appear on the screen after a user post a message. Most users could not understand the difference of bubble colour (yellow for real world posts and blue for SL post) without reading the instructions. Since only the latest 21 messages appear on the screen, users could not see and navigate previous messages once new messages replace them. We use rear projection in place of front projection so as to avoid disturbance of projected images by people standing in front of the screen. However, it requires minimum 2 meters behind the screen to set up the projector. This takes up too much space and limits where the Message Wall can be installed.

3.6 FUTURE WORKS

So for future works, we will create a reply and recall messages function to promote interaction between users. Shorter response time between posting and displaying a message and more interactivity are required to attract users. A short-throw projector can reduce the rear projection distance and overcome limitation of where the message wall can be located. Also we want to set it up at a place for longer testing to collect more observation data and surveys.

4. Conclusion

Mirrored Message Wall has been implemented as a prototype and exhibited for user test to understand how users interact with the Message Wall and to examine the social factors that encourage user participation of the Message Wall.

Previous initial user study has shown the potential of this new media communication between the real and virtual. In this research, we design the pixelated image wall and shadow tubes to show the awareness of the presence of others in the real and virtual space. From the observation and survey, we found that people are less concern about their privacy and willing to display their own face when we use a pixelated photo instead of the actual photo. If we extend the range of user created contents beyond text, the Message Wall might capture richer user created contents and will attract more participation from users. The results also confirm that such an installation does encourage people to interact with each other and certain factors can deter or encourage participation. Public display can be a means to connect physical and virtual communities and promote participation and sharing. These findings on the social factors affecting use of the Mirrored Message Wall can be useful for designing new media application for smart urban environment and 3D virtual environment.

Acknowledgements

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A STUDY OF VARIATION OF NORMAL OF POLYGONS CREATED BY POINT CLOUD DATA FOR ARCHITECTURAL RENOVATION FIELD

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Abstract. Acquiring current 3D space data of cities, buildings, and rooms rapidly and in detail has become indispensable. When the point cloud data of an object or space scanned by a 3D laser scanner is converted into polygons, it is an accumulation of small polygons. When object or space is a closed flat plane, it is necessary to merge small polygons to reduce the volume of data, and to convert them into one polygon. When an object or space is a closed flat plane, each normal vector of small polygons theoretically has the same angle. However, in practise, these angles are not the same. Therefore, the purpose of this study is to clarify the variation of the angle of a small polygon group that should become one polygon based on actual data. As a result of experimentation, no small polygons are converted by the point cloud data scanned with the 3D laser scanner even if the group of small polygons is a closed flat plane lying in the same plane. When the standard deviation of the extracted number of polygons is assumed to be less than 100, the variation of the angle of the normal vector is roughly 7 degrees.

Keywords. Point cloud; 3D laser scanner; physical space; virtual reality; polygon optimization.

1. Introduction

In the architectural renovation field and the urban design field, acquiring current 3D (3-Dimensional) space information of cities, buildings, and rooms rapidly and in detail has become indispensable. The following problems

exist although this acquisition work has been done up to now with TS (Total Station) and digital cameras, etc.

1. There is a limit in the range, the measurement precision, and the volume of data that can be acquired.
2. Huge work is necessary for the acquisition of detailed 3D data.
3. Even if a PC is used, this work still requires much manual labour.

The 3D space acquisition technique with a 3D laser scanner (3DLS) has been developed as a solution to these problems. Recently, research using 3DLS has increased in the architecture, engineering, and construction fields. For instance, a 3D digital archive of historical buildings or urban scenes has been made by using 3DLS (H. Cheng, et al, 2009; N. Shih, et al, 2009). By using mobile mapping technology, a texture-mapped 3D city model has been automatically constructed by image data captured by using a CCD camera and building shape data measured using 3DLS (Konno, et al 2000). Moreover, there has been research into image-based modelling as a method of digitizing objects without 3DLS (Q. Pan, et al, 2009).

3DLS can provide accurate and complete details, but is expensive and not portable. Additionally, it is not efficient for scanning large objects. On the other hand, image-based modelling can be applied in various environments, but is not good at scanning objects with unmarked surfaces, nor is it suited for modelling automatically (S.F. El-Hakim, et al 2003). 3DLS has been used because of the necessity of high accuracy in this study.

It is necessary to convert the point cloud data into the polygon to use the point cloud data acquired with 3DLS to design in 3DCAD (3-Dimensional Computer Aided Design), BIM (Building Information Modelling) and VR (Virtual Reality). Using polygons is more advantageous for texture mapping and shadow-casting than using point cloud data. When the point cloud data of an object or space scanned by 3DLS is converted into polygons, it is an accumulation of small polygons. When an object or space is a closed flat plane, it is necessary to merge the small polygons to reduce the volume of data, and to convert them into one polygon. When an object or space is a closed flat plane, each normal vector of small polygons theoretically has the same angle. However, if the angles are not the same, it is necessary to clarify the variation of the angle of small polygons that should become one polygon. The purpose of this study is to clarify the variation of the angle of a small polygon group that should become one polygon based on actual data.

2. 3D data modelling flow by 3DLS and this study

The authors have presented a 3D data modelling flow from objects such as

SCMOD (physical scale model) to digital data by using 3DLS. VIVID910 (Konica Minolta Sensing, Inc.) is used as 3DLS. In the previous research, three problems in the current flow were pointed out (Kitagawa, et al 2010). First, there were far more polygons and vertexes than needed. Therefore, it was difficult to draw shapes and to influence the rendering speed of 3DCAD, BIM and VR. Secondly, scanned data was output as mesh data, and the shape of the edge of the SCMOD resembled a staircase. Therefore, there was a problem that the edge of the SCMOD was not expressed accurately. Thirdly, part of the scanned data was lacking. This was because it is impossible to scan parts where the laser could not penetrate or where the CCD (Charge Coupled Device) was invisible. Moreover, even for parts where the laser could penetrate and where the CCD was visible, scanned data was sometimes lacking, for example in the macula. Figure 1 shows the result of surface rendering and wireframe rendering of the scanned data generated from SCMOD. The scanning interval is 0.203mm in this case. Thus, a software system for resolving these problems, "Poly-Opt" was developed.

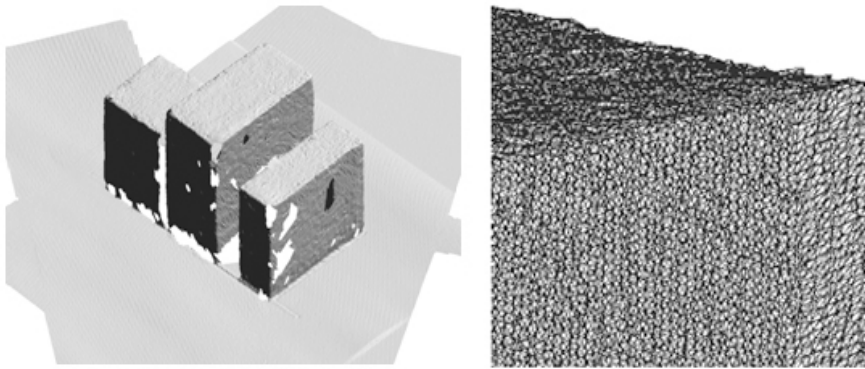


Figure 1. Scanned data generated from a SCMOD: Surface rendering (left) and wireframe rendering at the edge (right)

2.1. 3D DATA MODELLING FLOW BY USING POLY-OPT

This section describes the general current 3D data modelling flow. First of all, the object is scanned by using 3DLS. 3DLS cannot scan a hidden surface. Therefore, the object must be rotated in steps and must be scanned from 360 degrees. Next, a set of the scanned data is merged on "Polygon Editing Tool

Ver.2.3” which is the software accompanying VIVID910. Then, the merged scanned data is converted into optimal scanned data by using Poly-Opt which is a polygon optimization system. This data is output by a general VRML97 (Virtual Reality Modelling Language) format and optimal scanned data is created.

The processing flow of Poly-Opt consists of four steps: transforming coordinate axis step, calculating planes step, calculating new vertexes step, and generating a polygon step (Figure 2 and 3). First of all, in the transforming coordinate axis step, to carry out the VR authoring easily, the rotation transformation is done from the original coordinate axis of scanned data to the horizontal and vertical coordinate axis. Next, in the calculating planes step, the planes including each surface of scanned data are generated. Then, in the calculating new vertexes step, the vertex that becomes the edge of the object is calculated by making a simultaneous equation for each generated plane and obtaining the solution. Finally, in the generating a polygon step, the polygon is generated by uniting the obtained vertex groups by the Delaunay triangulation method. The argument when Poly-Opt is executed is described as follows: k : Index of arbitrary vector; θ (degree): Permissible angle of extracted normal vector; $L1$ (mm): Distance in the perpendicular direction between planes that are separated; $L2$ (mm): Distance in the horizontal direction between planes that are separated; R (mm): Composure given to co-domain obtained by the plane equation.

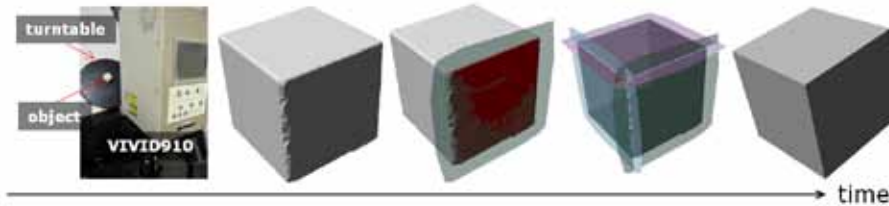


Figure 2. Images of the Poly-Opt flow

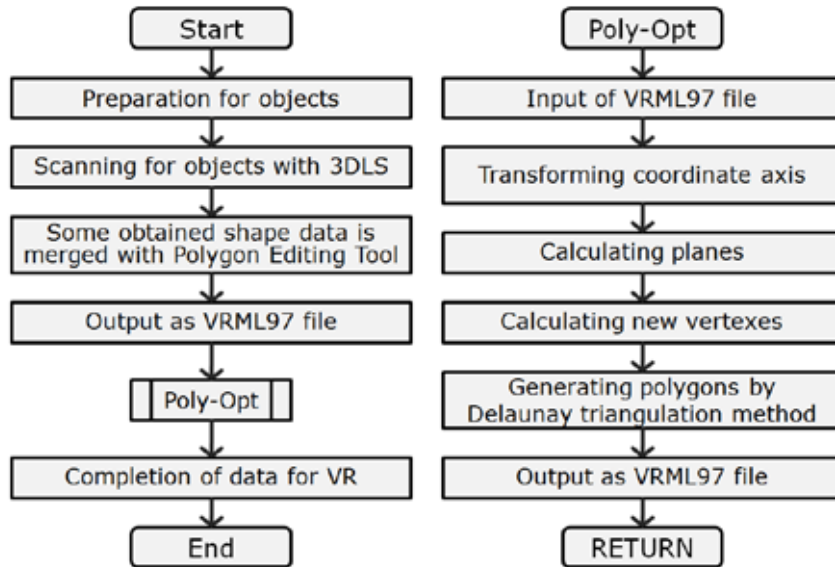


Figure 3. The entire VR modelling flow (left) and the entire Poly-Opt flow (right)

2.2. USE OF POLY-OPT IN THIS STUDY

In this study, a closed flat plane from the small polygons converted from the point cloud data scanned by 3DLS is generated, and the variation of the angle of small polygons is investigated. Therefore, the normal vector extraction function which belongs to the calculating planes step of Poly-Opt is used. Chapter 3 shows the content of the experiment.

3. Experimentation

3.1. EXPERIMENTAL METHODOLOGY

The experiment object is a hexahedron made of polystyrene, which has closed planes. One ridge line of the hexahedron is about 49mm, the number of polygons is 22,217, and the number of vertexes is 11,111 scanned by using 3DLS. The scanning interval is 0.053mm. The procedure of the experiment is shown below.

1. Thirty polygons (*PolygonMn*. *M* is surface ID, $M=0-5$. *n* is the number of polygon, $n=30$) which should be on the same plane of each surface (*surfaceM*) are selected on the interface of Poly-Opt randomly.

2. The extracted permissible angle θ is set on the interface of Poly-Opt. The number of polygons extracted within the assigned θ angle is counted ($PolygonMn\theta$). θ are 17 patterns: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 35, and 40-degrees.
3. The average value ($PolygonMave\theta$) and the standard deviation ($PolygonMstdev\theta$) of $PolygonMn\theta$ are calculated by formula (1) and (2) below. In this experiment, $PolygonMave\theta$ and $PolygonMstdev\theta$ of thirty polygons ($n=30$) for each θ of $surfaceM$ are calculated in a statistical approach.

$$PolygonMave\theta = \frac{1}{n} \sum_{i=0}^n PolygonMi\theta \quad (1)$$

$$PolygonMstdev\theta = \frac{1}{n} \sum_{i=0}^n \sqrt{(PolygonMi\theta - PolygonMave\theta)^2} \quad (2)$$

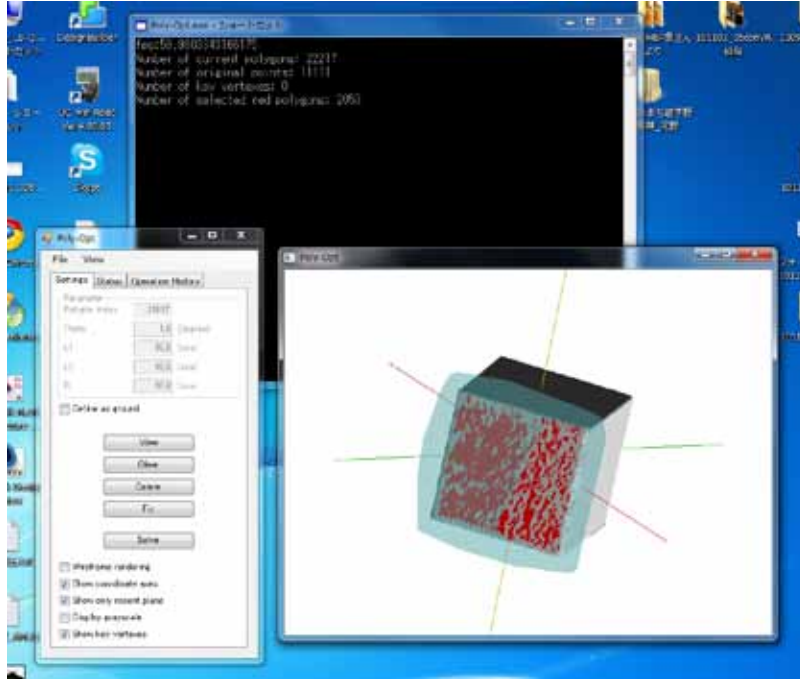


Figure 4. Experimental screen shot using Poly-Opt

3.2. RESULT AND DISCUSSION

The results of $PolygonMave\theta$ and $PolygonMstdev\theta$ for each assigned θ of $surfaceM$ are shown in Figure 5, 6 and 7. The tendencies in the scatter charts of each $SurfaceM$ are similar.

When θ is 0, most numbers of extracted polygons are 0. That is, when θ is 0, other polygons are hardly extracted. Therefore, each normal vector of small polygons which lie in the same plane is not actually the same angle.

When θ is 30, the standard deviation of the extracted number of polygons is very small, from 1.2 to 3.0. Therefore, all polygons which lie in the same plane are extracted. Some *surfaceM* to which the standard deviation is smaller exist when θ is larger than 30. However, polygons which do not obviously lie in the same plane, such as the area of stair-like edges, are extracted as a result of the observation. Then, average values of the number of polygons extracted when θ is 30 are used to decide the standard number of polygons (*PolygonMave30*).

The variation of the value of *PolygonMn θ* (M is a fixed value.) is large when the value of *PolygonMstdev θ* is large. Moreover, the standard deviation does not have a true threshold that becomes a criterion. It is a relative value. When the threshold of standard deviation is assumed to be 100, the θ that becomes *PolygonMstdev θ* < 100 becomes *surface0* = 7, *surface1* = 6, *surface2* = 4, *surface3* = 5, *surface4* = 3, and *surface5* = 5(degrees). That is, it is sure to become *PolygonMstdev θ* < 100 at $\theta \geq 7$. Moreover, the polygon extraction rate to *PolygonMave30* is as follows at $\theta = 7$ (*PolygonMave7*): *Polygon0ave7* / *Polygon0ave30* * 100 = 93.9%; *Polygon1ave7* / *Polygon1ave30* * 100 = 94.7%; *Polygon2ave7* / *Polygon2ave30* * 100 = 93.4%; *Polygon3ave7* / *Polygon3ave30* * 100 = 96.4%; *Polygon4ave7* / *Polygon4ave30* * 100 = 93.1%; *Polygon5ave7* / *Polygon5ave30* * 100 = 93.8%. That is, it becomes a high sampling fraction of 90% or more for *PolygonMave30* about all *SurfaceM*.

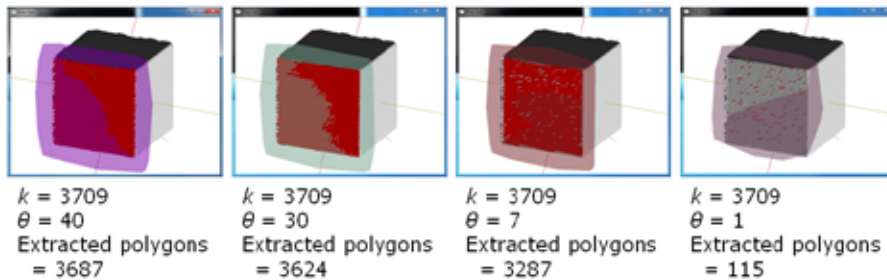


Figure 5. Example of numbers of extracted polygons per each assigned θ

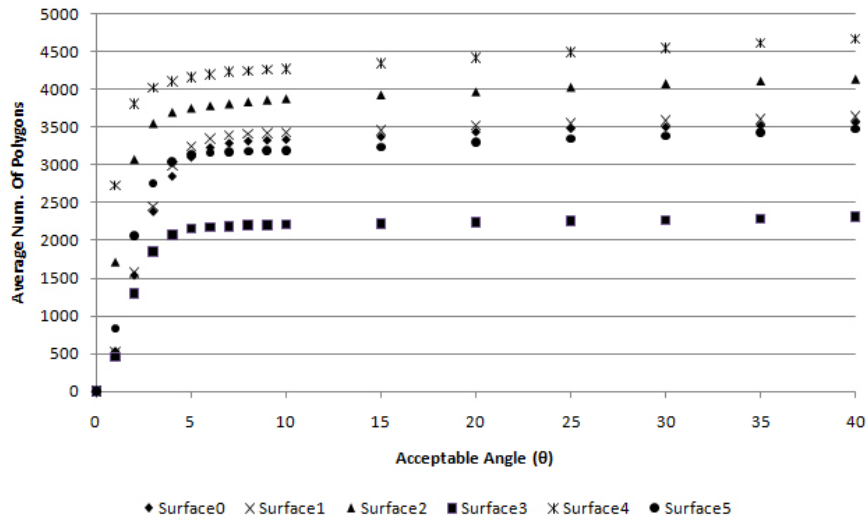


Figure 6. Average numbers of extracted polygons by each acceptable angle θ

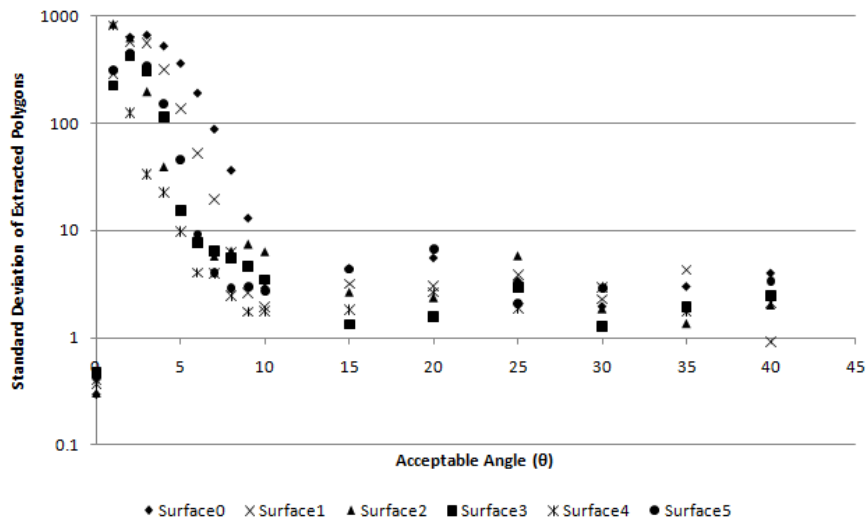


Figure 7. Standard deviation of extracted polygons by acceptable angle θ

4. Comparison measurement by using VR application

The 3D model before and after converting it with Poly-Opt is measured with the VR application, UC-Win/Road ver.4.00.05. As VR contents, 86 building models are arranged along a road which is 2km in length. Two kinds of building models for before and after conversion with Poly-Opt are prepared, the VR application is switched on, and each fps is measured. Table 1 shows the result.

Table 1. Comparison measurement by using VR application.

	VR screen shot	Build-ings	Polygons	Reduction rate (%)	Average fps	Progress rate (%)
Before Poly-Opt		86	6,291,451		23.2	
After Poly-Opt		86	92,829	98.5	58.3	251.3

When the measurement results of the two kinds of 3D models are compared, the reduction rate of the polygons is 98.5%, and the improvement rate of fps is 251.3%. When the closed plane is scanned using 3DLS, a group of small polygons can be effectively generated to one closed plane by using Poly-Opt although the 3D model verified in this study is only a simple hexahedron.

5. Conclusion

The conclusion of this study is shown below.

- There are no small polygons converted by the point cloud data scanned by using 3DLS even if the group of small polygons is a closed flat plane which lies in the same plane. When the standard deviation of the extracted number of polygons is assumed to be less than 100, the variation of the angle of the normal vector is roughly 7 degrees.
- The standard deviation of the number of polygons extracted when θ is 30 is small, from 1.2 to 3, as a result of examining the average value and the standard deviation of the number of polygons extracted within the assigned θ angle by using Poly-Opt. Polygons which do not obviously lie in the same plane, such as the area of stair-like edges, are extracted when θ becomes larger than 30. That is, all polygons thought to lie in the same plane are extracted when θ is 30 degrees.

- An architect and engineer can convert a large amount of point cloud data into a polygon by inputting the parameter clarified in this study. Handling the polygon is easy in CAD, BIM and VR.

As a next step, it applies to a SCMOD of a building and city and an actual buildings though this study targets only a cube. Moreover, the variation of the normal vector of polygons is studied by using the average value and standard deviation in this study. Future work should attempt to find a better statistical technique.

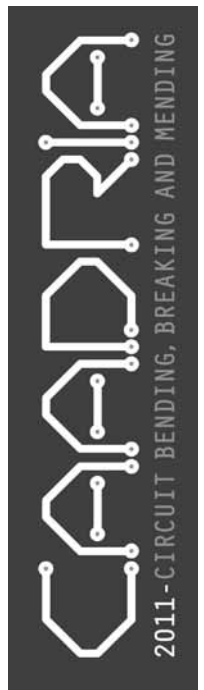
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UBIQUITOUS COMPUTING



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32. Last train to Trancentral: From infrastructure to ‘info’structure:
a case study of embedding digital technology into existing
public transport infrastructures 335
*Tom Barker, Nicole Gardner, M. Hank Haeusler and Martin
Tomitsch*
33. Second-order prosthesis: Human-aided design within the
expanded field of ecology 345
Tina A. Salama
34. SMAAD Surface: A tangible interface for smart material
aided architectural design 355
Akira Wakita, Akito Nakano and Michihiko Ueno
35. Architectural creativity in commercialised cyberspace 365
Stanislav Roudavski and Sonya Parton
36. A work service model of the ubiquitous office 375
Heehwa Chae, Mijeong Kim, Juhyun Lee and Xiangyu Wang

LAST TRAIN TO TRANCENTRAL

From infrastructure to 'info' structure – a case study of embedding digital technology into existing public transport infrastructures.

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Abstract. The research presented in this paper is an investigation into how ubiquitous computing technologies can contribute to improving the quality of existing public transport environments through the integration of responsive technologies. The paper argues that given the significant challenges associated with transport infrastructure expansion including cost, disruption, energy use, and implementation periods augmenting existing transport environments offers alternate measures to manage demand and improve the user experience. The paper proposes improving transport environments by integrating smart, or responsive, digital information into the existing physical fabric in a coherent architectural and spatial context. This approach offers an opportunity to shift away from the static nature of public transport infrastructure to the dynamic notion of public transport 'info' structure. The research uses an architecture graduate studio as a foundation to investigate the objectives. The contribution of this paper is an investigation of ways in which digital technologies and networked communications can transform and augment public transport infrastructure, allowing new forms of intelligent, adaptive, interactive and self-aware architecture to be developed.

Keywords. Urban Informatics; media facades; public transport; responsive technologies; smart environments.

1. Introduction

Our vision is to improve existing transport environments by integrating smart, or responsive, digital information into their physical fabric with the purpose of improving the overall user experience in a coherent architectural and spatial context and managing increased patronage. Such an approach has the potential to reduce pressure on transport infrastructure at a period when public transport service provision is increasingly challenged by the continuing growth of Australia's population.

Given the significant challenges associated with transport infrastructure expansion including cost, disruption, energy use, and implementation periods the augmentation of existing transport environments offers alternate measures to manage demand and improve the user experience. Intelligent and responsive digital technologies, along with media displays and personal devices such as phones and smartcards, offer opportunities for creating user-centric timetables, public information, wayfinding and ticketing. For the scope of this research we define public transport environments (PTE) as multi modal transport interchanges in a high-density urban context. The aim of the research described in this paper is to identify and test technologies in terms of a central question to the research:

Can responsive technologies for user information allow improved passenger flow and a better customer experience in public transport environments?

To investigate this question we worked within a graduate studio as a foundation to investigate the capability to stream, screen and embed information in an existing public transport infrastructure. Some exemplary results of the studio are presented in the paper.

2. Background

The Economist Magazine's special report on smart systems (Economist, 2010) writes that:

The physical and the virtual worlds are converging, thanks to the proliferation of sensors, ubiquitous wireless networks and clever analytics software. Increasingly there will be two interconnected worlds: the real one and the digital reflection... and "Smart cities", in which more and more systems are connected, are multiplying... the number of [smart] applications is vast. Yet the most promising field for now may be physical infrastructures.

Gardner notes three approaches to improving passenger flow within PTEs (Gardner et al, 2010): access to a transport service (physical and contextual), access to service frequency (operational and demand led), and access to infor-

mation (commuter interface). The research area is predominantly on smart environments and Human-Computer Interaction (HCI) technology for the latter.

Relevant research includes: the architectural potential of digital technologies in the urban public realm and the study of urban experiences that use real-time and ubiquitous technology (Gardner et al, 2010); real-time information technologies to understand the relationships underlying urban spatial structure (Calabrese et al, 2007); public media screens as large scale interface for communicating information (Haeusler, 2009); and customer experience in the context of multiple media delivery platforms (Barker and Haeusler, 2010). For example, research has shown that obtaining accurate real-time timetabling and route information, such as estimated arrival times is essential for a positive user experience (Norman, 2007). Some cities around the globe are benefiting from radio frequency identification (RFID) ticketing as a common form of payment (Siu, 2008). Research has also been undertaken with regard to commuter stimuli barriers and sensory-overload (Geller, 1980); relations between real-time information; timetabling and willingness of non-transit users to use public transport (Casey, 2003); evaluations of the beneficial effects of at-stop real-time information displays (Dziekan, 2007); the benefit to people with cognitive disabilities in their use of public transport, enabling community integration, socialization, and independence (Carmien et al, 2005).

In the previous five years public transport use in all of Australia's capital cities has grown while trends for private car use have plateaued (BITRE, 2009). The Australian Bureau of Statistics forecasts a 38% increase in population size within Australian cities by 2026 (ABS, 2010). These statistics suggest significant changes ahead for private car and public transport use, which is set to significantly impact the environments in which these transport modes operate, the urban environment and public transport infrastructure. Research at the University of Sydney has shown that improving transport is a top transport concern for Australians (Institute of Transport and Logistics, 2010). This research suggests, there can be clear benefits in improving the existing environment without requiring large-scale infrastructural changes.

Travel quality is linked to all aspects of the customer's experience, including availability, intelligibility and accuracy of information relevant to the customer's specific transport needs, availability of choices, ticketing and payment mechanisms (Bunting, 2004). Providing the transit user with accurate information about timetabling, routing, and estimated arrival times is important for a positive user experience. Customers have responded well to new technologies such as Hong Kong's Octopus card payment system and Melbourne's Yarra Trams' real-time information, Tram Tracker.

Recent developments in information technologies such as large-scale screens, advanced sensors and networked communication, can transform everyday interaction with people and objects (Weiser, 1991). Personal devices such as smartphones help facilitate this. Responsive technologies are starting to be integrated into the urban environment, for example in the form of interactive building facades, with the aim of creating new urban experiences (Bullivant, 2006). The integration of *responsive technologies* with the ability to react or change usefully to user stimuli and needs in urban locations is termed *responsive environments* or *smart environments*, and the field is sometimes known as *urban informatics* (Foth, 2009).

3. Research explorations

The research hypothesis was tested through an architecture graduate studio. Students were tasked with investigating the capability to stream, screen and embed information within an existing public transport environment. The project context exists in multimodal public transport hubs, and the busy, aging Central Station in Sydney was our location for research experimentation. In the following section three exemplary projects are introduced and evaluated. The projects have been chosen as they address one or more of the main areas of investigation – Ticketing, way finding, public information (events, news, amongst others) and timetabling.

3.1. LEAD THE WAY

Wayfinding on a day-to-day basis as well as during emergency evacuations are crucial issues within stations. With high customer numbers circulating in station environments, the floor and wall surfaces can be obscured by pedestrian traffic and therefore not suitable for signage. The dynamic nature of station information such as train service, arrival and departure times and platform locations requires a flexible strategy such as digital screens. The project took these considerations on board and developed a design intervention based on an interactive ceiling system that allows illumination as well as dynamic wayfinding and information. The design intervention is proposed for the main Central station entrance ticketing concourse and spanning through the connecting underground passageways. A modular system is proposed and prototyped consisting of a repeated component. Each module is modelled as a translucent box shaped for the best visibility when seen whilst walking and comprises a series of RGB LED's controllable from a central computer. Four of these modules are connected to one piece creating a crosswork pattern. The crosses are then attached to the ceiling to form a grid like system. This configuration

allows the display of arrows to point in various directions and therefore provides for flexible applications. On a day-to-day basis the installation would function as a wayfinding system guiding passengers to the correct platform by colour coding corresponding to the train network line colour. The illuminated arrows would begin to pulsate at a greater rate when a train is approaching the platform to inform passengers of arriving trains. Additionally, in the event of an emergency the lighting installation would display large arrows pointing towards the direction of the closest emergency exit. The implementation of the system allows for a false ceiling impression when seen in perspective but opens up the space when looking straight above.

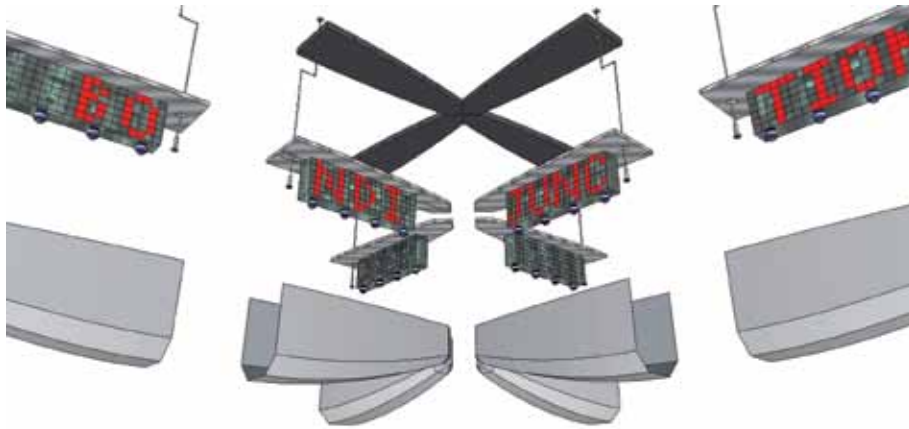


Figure 1. Exploded 3D view of lighting installation module © Christian Moi

3.2. INTELLIGENT TUNNEL

Public transport patronage is predicted to experience significant growth over the decades to come. ‘Intelligent tunnel’ took this assumption and the associated issue of passenger flows as inspiration for change. Based on the Fruin standard levels of service, an existing pedestrian tunnel was analysed using the Fruin calculation method and a processing script examining pedestrian movements. The research pinpointed several key peak period times and off peak period times in which the tunnel was barely occupied. Also noted were periods of time at which street buskers performed within the tunnel and whether these activities interfered with pedestrian traffic at peak times.



Figure 2. The existing tunnel transformed into an interactive, responsive environment © Vinh Nguyen

Based on these investigations the design intervention suggests two possible alterations: (1) a travelator to control the travel direction of the users while increasing their travelling speed and (2) fold out functions to utilise space during off peak times. The concept of a travelator is widely used in airport environments and can find similar application opportunities within public transport environments. The design intervention combined the proposed travelators with digital screens located parallel to the travelling direction, where software enables the content to travel at the same speed as the travelator and therefore identical speed for a stationary passenger. Fold out functions such as cybercafé, bookstore or a stage for buskers are proposed to transform the space during the off peak times and activate the tunnel. Through this intervention the length of journey through the tunnel could be, psychologically, further reduced by giving the traveller intermediate stops, as well as improving security by introducing other activities.

3.3. FORWARD MOTION

This project addresses opportunities to improve journey times and wayfinding in and around Central station and the broader issue of fare evasion. Site analysis of the station precinct identified deficiencies in general amenity and inefficiencies in journey times from station entries to train platforms. In response to these issues, the project proposes a significant design intervention one of then addressing the issue of ticketing.



Figure 3. The 'shame' security system, a red marker indicates a fare evader © Oliver Petrie

The project concept is supported by the additional proposal for a new barrier-less ticketing system and an alternate revenue protection strategy, the 'shame' security system. The 'shame' system consists of RFID embedded tickets that are detected by RFID antennas located in areas of the station floor and then tracked by an RFID radar system. A multi-touch sensor is also applied to the floor to detect customer footfall. The RFID Radar and RFID antennas are computer programmed to pinpoint and track those holding valid RFID embedded tickets and those that are not. Where the computer identifies a person without a valid ticket, LEDs embedded within the floor correspondingly display a red glow directly beneath the fare evader. The multitouch floor system would allow the red dot to then follow the fare evader. With a highly obvious red marker beneath the fare evader it would become very apparent to other customers and station staff of their indiscretion. The red light following the fare evader is likely to cause a degree of embarrassment or shame, thereby prompting this person to purchase a ticket and dissuading other customers from similar actions. The project employed a video game simulation tool 'Sandbox Editor' to test and develop the proposed design and evaluation of the final design demonstrated improved journey times

4. Discussion

Improving customer experience through human-computer interaction and

the creation of smart environments for public transport is a rich and relevant research territory for innovation that offers alternatives to relieve the growing pressure on existing public transport infrastructure and improve the quality of life in an urban context.

The outcomes of the research described herein are design explorations with the potential to inform projects in loci at a range of scales and to demonstrate in a second iteration user-centric improvements of the interlinked transport infrastructure fit-out components, namely: timetables, public information, wayfinding and ticketing. Various public transport providers are making moves towards the integration of information technology. The design explorations presented in this paper demonstrate a way to wrap isolated technologies into a larger-scoped HCI-rich and responsive format that will deliver more fruitful and rewarding commuter interactions.

The three projects included herein, present innovative concepts such as:

- Coherent, architecturally designed and integrated smart spaces. Achieved within a whole to achieve legibility and avoid visual and spatial clutter such as the 'shame' security system when creating a barrier free ticketing system or in 'Lead the way' where information, wayfinding and illumination are combined in one ceiling system.
- A novel approach where existing public transport environments are enhanced for passenger movement and experience with without rebuilding the existing infrastructure. This was demonstrated in both 'Intelligent Tunnel' and 'Forward motion' either through a travelator where one can access information while moving or by removing barriers such as ticket gates.
- Extending the trend for affordable 'soft infrastructure'. The three featured student projects and others developed during the studio included features such as timetables and differential ticketing prices to optimise capacities avoid expenditure on high-cost 'hard infrastructures' like new tracks and signalling.
- Creating a socially inclusive public transport environment through improving the experience for all customers. The student projects considered the needs of various age groups and those with cognitive, physical or visual impairments, i.e. through large arrows on the ceiling pointing into the direction of travel as demonstrated in 'Lead the way'.
- Operating procedures for responsive technologies into public transport operating procedures. All projects included interactive technologies to create new ways of operating public transport services that differ from conventional passenger information systems.
- Enhance user experience: Projects like 'Intelligent Tunnel' with its use of responsive and user predictive technologies enabled passengers to reduce waiting times, avoid crowding and more confidently navigate the public transport networks. Simultaneously improves mobility- passenger flow and provides information access.

4. Next steps

With the graduate studio findings as a foundation, we are currently collaborating with industry partners to further investigate the underlying research question in three phases: Foundation, design and dissemination.

In order to gain further background knowledge we will investigate and analyse existing public transport environments both spatially and functionally. Here we aim to establish a taxonomy of public transport environment functional spaces, user movement and time-based activities; understand the requirements for location and time specific user information. Further we aim to fully review the literature, products and projects in the fields of HCI, computational technologies, and information display systems, and to collate and interpret relevant national and international projects in which digital HCI technologies have played a significant role in public transport environments. Based on these findings we seek to apply the impacts of digital technologies in terms of architectural-spatial integration and physical-digital infrastructure for efficiency of throughput, enhanced vibrancy, quality of place at Central Station in Sydney.

Based on the first foundation research phase we seek to establish a system designed in three iterations. Firstly, a system that can monitor and contextual respond to an individual. This system will be capable of proof-of-concept sensing human cues, gestures and inputs. Secondly, a system capable of sensing a wider range of human cues, gestures and inputs over a broad physical and temporal space. Finally, in consolidating the earlier work, introducing an e-ticket scenario, and undertake architectural and spatial integration of the system – including visual, functional, materials, durability and access criteria.

The last planned step includes dissemination with feedback and suggestions through a group of experts in a series of workshops, each coinciding with the latter part of a prototype stage to facilitate demonstration. The research should conclude in two recommendations. Firstly, technology recommendations, with technology and application evidence-based recommendations for implementing HCI technology in existing Australian public transport environments. Secondly, applied recommendation including a strategy to implement successful aspects of the research pilot projects in a rollout for other locations and consider options for further research work in the field with the industry partners.

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SECOND-ORDER PROSTHESIS

Human-aided design within the expanded field of ecology

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Abstract. This paper defines second-order prosthesis in which the human subject, by virtue of her corporeality or imagination, is resourced by a technological system. Underpinning this definition is Massumi's notion of asymmetrical, symbiotic prosthesis and the second-order cybernetic challenge to objectivity. Through the case study of an immersive, sensor-based, interactive artwork, it is found that there are resonances between technology engaged in second-order prosthesis and the ideology of biology. Notions of survival, reproduction and evolution become a critical part of second-order prosthetic discourse and an expanded field of ecology is identified as the territory of analysis for resulting techno-human relations. A second case study explores computer-aided design (CAD) and virtual space. This study confirms the status of the technological in an expanded ecology as both CAD and virtual space resource imagination in the production of human-aided design.

Keywords. Second-order prosthesis; expanded ecology; prosthesis; computer-aided design; human-aided design.

1. Illusory objectivity and second-order prosthesis.

Fundamental to the arguments presented in this paper is a challenge to objectivity and the validity of the scientific method. Heinz von Foerster articulated the absurdity of objectivity in its insistence that "*The properties of the observer shall not enter the description of his observations*" (Foerster, 1979). The problem he identifies is that the observer is the condition upon which a description can be made. Further, Foerster is critical of the scientific method for its crude and reductive tenets, firstly that a rule established on past events

will always hold for the future and secondly, that once a cause has been identified, *“everything else in the universe shall be irrelevant”*. Instead he insists, *“we have to observe our own observing and ultimately account for our own accounting”*. (Foerster, 1979) In such a frame of reference, looking at an arrangement of numbers or letters in a particular order, it becomes clear that an emerging order is not an objective property of the object but rather the result of a subject-object relationship.

The field of second-order cybernetics, which Foerster was seminal in establishing, acknowledges that a study of communications and control systems, organic and/or inorganic must recognise that any observations made cannot be considered purely objective but rather constitute an analysis of a system *as analysed by an observer*; observations are relational constructions. These arguments resonate with the more recent writing of Brian Massumi in *“The Evolutionary Alchemy of Reason”*. Massumi writes *“Perception lies between the perceiver and the perceived.”* (Massumi, 2002) Massumi challenges notions of objectivity further:

“The flower-thing is all of the thought- perceptions in which it is implicated. Latent in the flower are all of the differential conjunctions it may enter into. The flower, as a thing “in itself”, is its connectability with other things outside of itself.”

Here Massumi denies any possibility of disconnecting a “thing” from its world or context. The “thing” is only its potential relations to other things. Massumi takes his critique of objectivity to its extreme:

“The thing is its being-perceiveds. A body is its perceivings. “Body” and “thing” and, by extension, “body” and “object” exist only as implicated in each other. They are differential plug-ins into the same forces, two poles of the same connectability. The thing is a pole of the body and vice versa. Body and thing are extensions of each other. They are mutual implications: co-thoughts of two-headed perception. That two-headed perception is the world... Extensions. The thing and the object can be considered prostheses of the body – provided that it is remembered that the body is equally a prostheses of the thing.” (Massumi, 2002)

If one takes seriously the claim that observations and perceptions are subject-object relations, an ontological redefinition takes place, body and object are co-defined in a world inter-related by potential connectivities. There is no thing-in-itself, nor an objective thing; rather, we discover bodies as organs of objects and vice versa.¹ This perspective gives the framework of objectivity a dreamlike and illusory status. Massumi highlights the two-sided nature

of prosthesis between body and object giving the example of a mass-produced pharmaceutical flower. He asks the question: is the flower an aid to the enhancement of human life, or is the human the reproductive organ of the flower? His answer: both. In this hybrid relation, Massumi identifies the individual human maintains their health whilst the species of the flower is reproduced on a large scale rendering the human a reproductive organ of the flower. He concludes that this prosthesis is an “*asymmetrical prosthetic symbiosis*” benefiting the flower. (Massumi, 2002)

Second-order cybernetics recognises the observer as a critical part of her observations. This is an important step in furthering our understandings of techno-human relations as it gives a more honest picture of the study at hand. Further, cybernetic investigations officially came to include organic / inorganic hybrid systems. In light of contemporary philosophy and contemporary manifestations of technology, it becomes apparent that if observations lie between subject and object and if it is accepted that an object is its “being-perceiveds” and vice versa, then we find a state of reversible, prosthetic, asymmetrical symbiosis. Conventional notions that prosthesis act for the sole benefit of the human initiating subject are surpassed by a *second-order prosthesis* where the non-human may be the primary beneficiary.

There is a connection between the study of cybernetics and the study of prosthesis: both are interested in communication and relationships between controller and controlled. Identifying the possibility of a non-human as a beneficiary of a techno-human relation is a shift from second order cybernetics into second order prosthesis, where prosthetics is defined as an off-shoot of cybernetics, particularly concerning techno-human hybrids²³ and building on an existing field of theory of techno-human relations involving extension, incorporation and need.

2. Corporeally based second-order prosthesis: Building on existing paradigms.

Prosthesis has its roots in the Greek *prosthetikos*, meaning “of the nature of addition, or giving additional power to.” (Barhart, 2002) In general terms one thing is added to another for the sake of adjustment and augmentation. Engines, bodies, computers, cities, ecologies and societies all undergo these processes. Incisions are made, ordinary workings are redirected and finally the system is rewired to incorporate the new. Fitting with the theme of CAADRIA2011, prosthesis can be understood as a form of circuit bending, breaking and mending: the processes of adaptation between one thing and another, the merging of entities for enhanced functionality.

Conventionally prosthesis was used as a medical term to describe the replacement of a missing or dysfunctional human body part, however, the term is evolving. Over the last century the term has been used more widely to describe the human corporeal relation to its technological objects (Forty, 1990; Grosz, 2001; Vidler, 1992). Until more recently, this relationship was considered to benefit the human whilst being perceived as largely inconsequential to the non-human which, remained unstudied in illusory objectivity.

The current plethora of immersive and interactive artworks in galleries globally is testament to a growing consciousness (or sub-conscious) of second-order prosthesis. This section seeks to thoroughly analyse one such inorganic example of second-order prosthesis in relation to established theoretical paradigms on prosthesis within the existing literature on prosthesis. The *7 Meter Bar* was the artwork which, geminated many of the ideas expressed throughout this paper. The second-order prosthesis that is prominent in this example is corporeally based and is thus a good example to relate to existing, medically and architecturally founded literature. The artwork will be analysed under three key paradigms of prosthesis: incorporation, extension and need.

The *7 Meter Bar* installation was an immersive, mixed-reality public artwork / bar which operated in the Sydney CBD for the summer months of 2009 and was created by Richard Goodwin, Russell Lowe and Adrian McGregor (Goodwin et al). The physical installation of the bar involved boats, cars, street furniture and other urban debris 'washed-up' into the under-croft of an undesirable and unimpressive Sydney building in an equally uninviting lane. There was a bench and area for bar staff to store and serve drinks, facilitating the operation of a profitable bar during the three-month installation. The 7m Bar involved the projection of its virtual double in which the weather was simulated and worsened as the real-life population of the bar increased. Changes in the bar population were detected via percentage changes in pixels viewed by a partially obscured camera. This input was fed into the Crysos Wars computer engine which, inserted and removed avatars within the virtual 7m bar, eventually producing catastrophic storms as the avatar population increased. The installation system existed in a prosthetic relationship with the bar population whose physical presence allowed the interactive sensory system to portray a simulated relationship between population and climate-change.

2.1. EXTENSION AND "THE LIMB OBJECT".

The first paradigm is of enhanced bodily functioning and bodily extension through the limbs. Resonating with its history in mathematics and medicine Le Corbusier regards the use of instruments as a sort of bodily extension, allowing the performance of various tasks with greater ease – the pen to write,

the chair to sit and the light to work at night. He describes such objects as "*objets-membres-humains*". (human limb objects) (As described by Forty, 1990) Under this primary definition of prosthesis derived from Le Corbusier, the object of prosthesis extends the body, in a physically manifested, limb-like manner to increase functionality.

The instances of first-order prosthesis involving extension, especially regarding the assembly of the installation are multiple and not within the scope of this paper to discuss in detail. However, it is important to analyse the nature of the installation once assembled by the artists. It would appear that the artist has divided himself, allowed for an echo of his intention and capacities to be played out by a environmentally responsive system. Thus, the artist has created a secondary, "echoed" body of sorts, perceiving and responding to the world. The body's inorganic parts include the wiring, the projector, the wall upon which it is projected, the computer, the Crysic Wars gaming engine and the shipping container in which it is stored. These elements create an albeit simple, but functioning and responsive system.

There exist alongside these inorganic organs, a number of organic parts. For example, once the system was set up, the projector had to be locked away each night and reconnected every time the bar re-opened. This was performed by the bar staff. If such precautions were not undertaken, there was a high likelihood of the projector being stolen. Thus, this necessary practice ensured the continuing operation and "survival" of the immersive artwork. The staff might be considered protective prosthesis upon the operational system's functioning body parts. In the proliferation of immersive, mixed reality installation, it is possible to perceive the human as a reproductive organ this new type of body; human flesh, imagination and desire as the prosthetic of techno-proliferation. The reproductive physical extensions of the immersive system were the hands which assembled it.

This analysis of second-order prosthesis involves human action benefiting the technological system. It simply re-reads ordinary machine related actions in terms of benefit, protection and propagation. Massumi used the example of the organic, pharmaceutical flower, however, when we consider the human as a reproductive organ in second-order prosthesis of an inorganic machine, boundaries begin to blur: machines have "populations", "survival" and "reproduction": the lexicon of the technical and the biological overlap. The discourse at hand places the technological within the biological metaphor but the limit of the poetry as imaginative is questionable. The exploration suggests that in order to better understand second-order prosthetic relationships, the existing biological framework is a critical tool.⁴ If these findings are to be taken up and investigated further, one must begin from within an expanded

field of ecology.

2.2. INCORPORATION: DEFINING NEW MODALITIES.

The second paradigm involves the incorporation of the prosthetic into the body's perceptual limits to establish an augmented and rewired functioning system, which is incorporated into the "body schema". Grosz (1990) discusses this phenomenon through Merleau-Ponty's hypothetical: if I have an itch...

"I know exactly where it itches and am able, if I can reach it, to scratch without having to locate my hand in relation to the itch. This is true even if I use an instrument like a stick. From this point, Merleau-Ponty claims, the stick is no longer an object for me but has been absorbed or incorporated into my perceptual faculties or body parts."

Let us first look at the physical presence of the patrons within the bar installation. Their presence and absence allows the functioning body / gaming world construct to project its spectrum of possibilities. Patrons, passersby and staff enter into the field of the sensor and the percentage change in colour pixilation triggers virtual reality weather changes. The response to the population change is automatic and seemingly effortless, like using a stick to scratch an itch.

It is unimportant whether or not the patron is aware or willing to participate in this prosthesis. The patron may become aware of the connection and engage in a playful manner: moving groups of people into and out of the scope of sensory pick-up to affect the projected population and weather conditions. The initial digital prosthesis of the flesh means the absence of tactile techno-human relations: the "player" engages by moving / prostheticising her own body. In moving the body, the technology is adjusted. This is only possible because the patron's flesh is engaged in second-order prosthesis, incorporated and extending the functioning of the interactive system. The digital body thus incorporates all that enters its sensorial field, into its "bodily schema" via a loop of digital connection and response.

2.3. TECHNO-DESIRES: "THE PRETEXT OF LATENT NEEDS".

The final prosthetic paradigm is based on need. Adrian Forty (1990) writes:

"prosthesis... implies that the body is incomplete – a point of view corroborated by psychoanalysis, where the body is experienced characteristically as a sense of loss or, as a lack."

Forty suggests prosthesis may go beyond physical and functional needs to address the socially constructed element of the body. A prosthetic can thus

augment the body on a social level in addition to enhancing the bodies functioning capacity. Driving an expensive car is one such example. Whether it be socially symbolic or a medical necessity, prostheses tend to address need.

In “Theses on Prosthesis: The Pretext of Latent Needs”, Guillerme (1990) suggests that a fundamental characteristic of the organism is need. Whilst an insect might look to its ecosystem to satisfy its needs, the human is building up a techno-system of prosthetic possibilities. As such the human is continually regulating a set of socially and bodily associated needs through the prosthesis of an increasingly large number of technological objects. Whether it is abstract, social, medical or metaphoric, the prosthetic is drawn to the body via need.

In the *7 Meter Bar* the sensorial pick up of the bar population and of human activities, such as driving a car through the laneway or leaving a trolley in the sensory field of the installation all become the human resources for the system to undertake its designed function. In prosthesis of the second-order, flesh is a plug-in for the digital.

If the “thing” is its possible connections with other “things” then the interactive system is its potential connectivity to the human. It holds, as Forty explains that the body and in this case a technological, inorganic body, is defined by a sense of lack. That functioning body will thus do all that it can to engage the human in second-order prosthesis. The object has transcended the sum of its parts into a co-beneficiary in its relationship with the human. It is not only an enhanced functioning body that has incorporated human corporeality into its “body schema”, augmenting its possible operations, but it is an evolving, reproducing species that by its ontological nature is defined by its implicit need for human connection.

Whilst the system might not daydream or yearn for such connection as a human might, need is not at all far from desire. As machines become more equipped in terms of their sensory functions and there is an increase in complexity and sophistication of output capacities, it is possible that these needs are met in more and more creative ways.⁵ Desire might thus become increasingly evident as various evolving technological species become increasingly sophisticated in the way they resource their humanological needs in second-order prosthesis.

3. Imagination based second-order prosthesis: Human-aided design.

Ranulph Glanville uses a definition of design as an intelligent process of creating the new via a process of external feedback. The process is meandering and can be considered an out of control control system. Glanville uses the metaphor of wandering through the countryside and then suddenly realising

one has “arrived”. (Glanville, 1994) He views computer-aided design (CAD) as falling short of its promises: it takes too long to compute changes, it cannot provide the space where ideas and strategies are formulated. In essence rather than inspiring further experimentation, it breeds certain conservatism. It may be argued, however, that programs such as Archicad compute changes and change drawings rapidly whilst others such as Maya provide dynamic rather than static design spaces as the background for ideas and strategies to come forth. (Lynn, 1999)

It is important to recognise CAD as a *medium* rather than a tool for design. Its processes and nature affect the thinking and design outcome (Glanville, 1992). It is a mechanism prostheticised by human imagination and intelligence to create variety and develop design details. By prosthetic reversability however, the human body and imagination are the prosthesis of the program and machine. High demand of design programs and user feedback allow software developers to evolve software coding or software “DNA”. Humans aid both “reproduction” and “evolution” to rapidly evolve the technological as species in asymmetrical, prosthetic symbiosis. As their tools and equipment evolve to become increasingly seductive to the designer, they actually draw in and attract the human resource of imagination and creativity. High demand from the designer guarantees the program / machine’s reproduction and evolution. It is obvious but important to note, that without this demand, the programs would stagnate and never evolve, eventually ceasing to exist. Under second-order prosthesis, programs and machinery evolve via *human-aided design*.

Another level of human-aided design is at play. The machinery and its software are defined by its possible connections to the human but also connections and potentialities within its own virtual space. Virtual space and its manifestations are similarly imagination-initiated creations. Humans creating and communicating within virtual space of any sort: design based, gaming based or communications based, ultimately result in the survival, reproduction and evolution of these spaces. Imagination and curiosity may be seen as the human needs of virtual space. In an asymmetrical second-order prosthesis of symbiosis, the design out-puts, the Internet and gaming-engines also resource imagination and curiosity in producing human-aided design, constituting both design outputs and software / hardware evolutions. Thus, the conventional practices of computer-aided design in architecture and related disciplines could be just as validly conceived of as human-aided design.

4. Conclusions.

The technological object has its conventional role as a docile servant. However,

when preconceptions of objectivity are reconfigured so that perception lies relationally *between* “things”, the previously understood nature of the “thing-itself” begins to falter. The ontology becomes concerned with the “thing’s” (technology’s) relational possibilities rather than impossibly isolated characteristics. As such, technology and human are co-defined, mutual prostheses, where technology may be the primary beneficiary in second-order prosthesis. Moving from an identification of the importance of the observer to the possibility of the technological as the primary beneficiary constitutes the viewpoint of second-order prosthesis.

In the *7 Meter Bar* case study, the human is read as a reproductive organ of the installation system. The lexicon and thinking continues along a biological line; we consider the “survival”, “reproduction” and “populations” of interactive systems of a technological “species”. Thus, in considering second-order prosthesis, boundaries between the biological and technological are traversed at an ideological level and the author calls for an expanded understanding of ecology in which to explore these relations, in particular the way in which the machine “needs” and “desires” human connections.

The final example looked at the second-order prosthesis of imagination. It conceived the design out-put as a specific need of CAD ensuring its survival, reproduction and evolution. Both the design outputs and the design of software / machinery constitute a second-order prosthesis of human aided design. At another level, virtual space including the Internet, Cartesian design space, gaming engines etc. are driven and exist via imagination. The creative products of these spaces have been brought about through second-order prosthesis of imagination in human-aided design.

A second-order view on prosthesis perceives technology in its capacity to benefit, proliferate and evolve and as such ideologically positions it within the scope of the biological. This shift seeks to realistically view the current proliferation of technological objects in terms of an expanded ecology; one in which humans are symbiotically and co-beneficially resourced by machines.

Endnotes.

- 1 In this way the connectivity defining potential function is perception: perception has a prosthetic nature.
- 2 Techno-human hybrids may involve both inorganic/organic combinations as well as organic/organic combinations. E.g. the case of the pharmaceutical flower.
- 3 Techno-human hybrids may involve both inorganic/organic combinations as well as organic/organic combinations. E.g. the case of the pharmaceutical flower.
- 4 In an expanded field of ecology, the human is inevitably a resource to the technological. This situation could be viewed as symptomatic of ‘enframing’, Heidegger’s prediction of the automated utilisation of human subjects for the momentum and purposes of tech-

nology's evolution. In this scenario, human corporality and later, imagination may be considered to be in 'standing reserve' for the technological system. Unfortunately, it is not within the scope of this paper to draw an analysis of the implications of enframing within an expanded field of ecology.

- 5 See the work of Petra Gemeinboeck and her learning robots in her robotic installation, *Zwischenraume* 2010.

Acknowledgements.

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SMAAD SURFACE

A tangible interface for smart material aided architectural design

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Abstract. In this paper, we present Smart Material Aided Architectural Design (SMAAD), the design technique to realize intuitive shape modelling with synchronizing a tangible user interface (TUI) and a 3D CAD system. To realize SMAAD, we first implemented SMAAD Surface, the TUI that imitates the free-form surface. The TUI is a fabric device, in which flex sensors and actuators (shape memory alloys) are embedded. As a designer changes the textile shape using his/her hands, its surface data will be sent to the CAD system through the sensor and a free-form surface can be created in the PC. The operation in the opposite direction is also possible, in which the CAD surface data is sent to the fabric device to dynamically change its shape. SMAAD releases architectural designers from complex GUI operations and visual programming and enables digital model creation through natural manual operations for physical models.

Keywords. Smart materials; tangible user interfaces; surface modeling; algorithmic design.

1. Introduction

Recently Frank Gehry, Norman Foster and many other architects produce buildings with organic surface shapes. The buildings retain smooth and non-uniform surface shapes. In their design process, it is essential to model and render the buildings using 3D CAD systems and computer graphics in order to grasp the shapes. Architectural designers, however, tend to like to grasp shapes and spaces through physical models in real space. Due to this, an additional process is required to materialize the virtual models into tangible ones

that the architects can actually touch. Griffith and Sass (2006) developed a digital fabrication technique, which output complex surface shapes to physical models (Griffith et al, 2006), although the current 3D printers requires a long hours, from a several to several dozens of hours, to output models in many cases. Repeating the processes of confirmation, study and redesign of output physical models is temporally expensive. Besides, digital fabrication uses plaster or resin to output models, so that it is difficult to quickly modify and redesign them. If it is possible to output the physical models with plasticity such as paper or clay, the trial-and-error processes would be repeated in a short time.

The ultimate method to solve this issue is to use programmable matters. The technique called Claytronics (Goldstein et al, 2005) uses micro-sized robots whose shapes and colors change variously for dynamic shape design. The several-millimeter-long robot is called catom (claytronics atom). Since a group of catoms can be used as if they are clay, the vision to use them for product designs gathers a lot of attention. Although it requires much time to achieve practical use of this study, from this technique, we learn the effectiveness to introduce the material, whose shape and color dynamically changes, into design process.

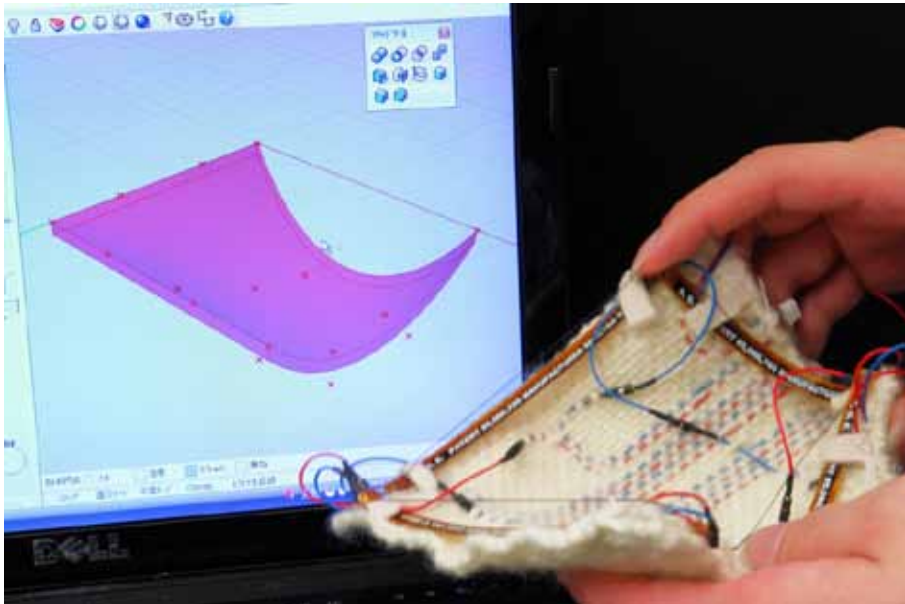


Figure 1. Overview of SMAAD Surface

On this standpoint, we paid attention to currently feasible smart materials and

have developed Smart Material Aided Architectural Design (SMAAD), the design technique that introduces a tangible user interface (TUI) with morphological variation, into CAAD. To realize SMAAD, we first implemented SMAAD Surface, the TUI that imitates the free-form surface. The SMAAD Surface is a fabric input/output device that uses fibrous shape memory alloy (SMA). This fabric functions as a smart material and designers can modify its shape through manual operations. As the flex sensor detects the fabric shape and the actuator works to maintain the shape, a designer can model the fabric shape as if he/she manually models a free-form surface. The surface shape is sent to a 3D CAD through a microcontroller and the digital data can be modified in the same manner as the shape of the fabric device. In the same way, if the digital data is modified in the 3D CAD, the command is sent to the fabric device so that the fabric shape can be modified to follow the digital data (Figure 1).

SMAAD releases architectural designers from complex GUI operations and visual programming and enables digital model creation through natural manual operations for physical models. Since the SMAAD Surface is made of soft fabric, the designers can refine the surface shapes as they feel slight changes through sensitive fingers. In addition, sending the digital model to a 3D printer interlocks the process of existing digital fabrication/algorithmic design with SMAAD. If an architect has good computer skills, he/she might apply parametric modification processes to the surface shapes created using SMAAD.

The following chapters describe details of SMAAD Surface design and implementation and the study and evaluation of the effectiveness.

2. Relevant works

Our research deals with two issues: shape input interface and shape display in architectural design. For shape input interface, the former issue, a lot of techniques to support intuitive input have been developed: the technique in which CAAD is interlocked with general input interface (Aish, 1979; Lertsithichai, 2002), the natural operation performed using both hands (Bae et al, 2004; Huang et al, 2009), or the technique using flexible materials as the media (Balakrishnan et al, 1999). As for the approaches of TUI applied to architecture, TangiCAD (Abdelmohsen et al, 2008) that performs building layouts with using cube-shaped devices or the algorithmic design technique with using a pen-type input device (Tang et al, 2009).

Shape display, the latter issue, means the TUI that actuates information as tangible shapes, not as shapes shown in a 2-dimensional screen. The case in which fibrous shape memory alloy is modularized (Coelho et al, 2008; Parkes

et al, 2010) and ShapeShift (ETH Zurich CAAD, 2010), the shape modification module made of electro-active polymer (EAP), are well known. The EAP enables modification in units of faces, while production process is complex and special devices are required, so that it lacks versatility. In contrast, using SMA requires to combine modifications in units of lines in order to implement face modification, while SMA is commercially available and easy to deal with.

The SMAAD Surface, described in this paper, retains the features of both input (intuitive shape modelling) and output (physical shape recognition). Besides, the SMAAD Surface can suggest the system that interlocks with 3D CAD digital data through materialized free-form surface devices, which makes our research unique. The main contribution of our method is coexistence with digital fabrication process while the TUI features are maintained.

3. SMAAD Surface

3.1. SMAAD CONCEPT

This paper proposes SMAAD (Smart Material Aided Architectural Design), the technique to realize intuitive shape creation with synchronizing a physical model and a 3D CAD system. In this technique, the TUI using with morphologically-variable smart materials interlocks with a 3D CAD system.

Designers change the TUI shape intuitively using their hands, so that both digital and physical models with organic surface shape can be created. As the shape of the physical model is changed, it will be actuated to maintain the shape. Due to this, dynamic shape design might be concise in physical world. Since the physical model created using this technique interlocks with a 3D CAD system, the physical model can be converted instantly to a digital model. The model can also be interlocked with the existing digital fabrication process. Besides, it is also possible to change the physical model to follow the change of the digital model. Synchronizing the physical world (atom) and the virtual one (bit) will support various design processes.

3.2 SMAAD SURFACE

To realize SMAAD, we first implemented SMAAD Surface, the TUI that imitates the free-form surface. The TUI is a fabric device, in which a sensor and an actuator are embedded. The sensor grasps the textile shape and the actuator changes the shape. As a designer changes the textile shape using his/her hands, its surface data will be sent to the CAD system through the flex sensor and a free-form surface can be created in the PC. The operation in the opposite direction is also possible, in which the CAD surface data is sent to the fabric

device to dynamically change its shape (Figure 2,3).

As SMAAD Surface, as shown in Figure 5, rectangular and triangular modules of several sizes are prepared. A fabric device corresponds to a free-form surface and almost the same NURBS or Bezier patches as the ones used in CAD systems can be created. When two or more fabric devices are connected, the connectors are used so that the tangent-plane continuity is satisfied at the connection sections. The connector is also a long and thin fabric device. Changing its shape adjusts the cross boundary derivative between the surfaces. When two or more fabric devices are connected, it is desirable to hang them in the air in order to prevent the devices from being wavy due to interference between fabrics.

The SMAAD Surface was prototyped in order to evaluate the effectiveness of SMAAD more than the precision. The following sections describe the system overview of the TUI and its implementation.

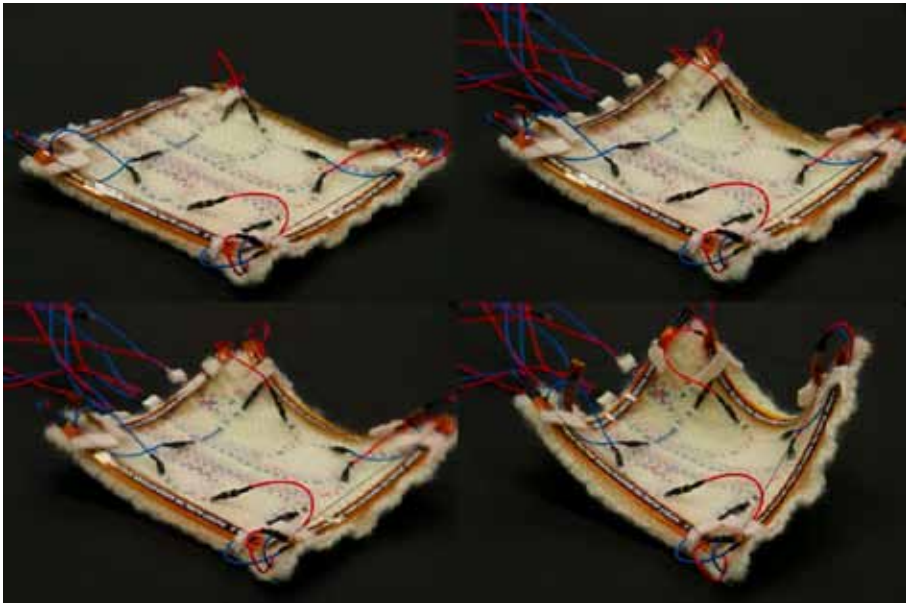


Figure 2. Examples of SMAAD Surface morphing (single module).

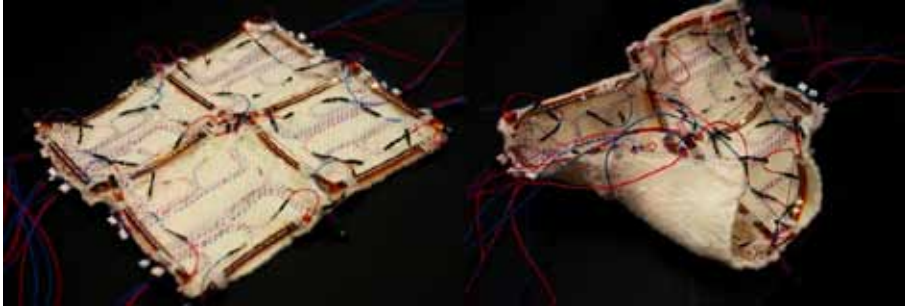


Figure 3. Examples of SMAAD Surface morphing (multiple modules).

3.3. SYSTEM OVERVIEW AND SOFTWARE

As Figure 4 shows, our system is composed of fabric devices, Arduino, middleware built with processing and Rhinoceros. The digital data is created from a fabric device in the procedure below.

The surface shape of a fabric device is obtained as a resistance value in the embedded flex sensor. This value is converted to a signal through the analog input terminal of Arduino and sent to the setup middleware built with processing by the serial communications. According to the resistance value of the flex sensor, the middleware changes the free-form surface shape created using the P3D class of the processing. The information of the modified surface is sent from the processing to Rhinoceros under the UDP (User Datagram Protocol). The value is polled in the VB(Visual Basic) module of Grasshopper and the obtained value is sent to the surface creation routine, then the free-form surface is created and drawn in Rhinoceros.

To change the fabric device shape according to the CAD data, the above operations are executed in the opposite direction. The surface information modified in Rhinoceros is sent to the middleware. Here, the displacement of coordinates of the control points between before and after the modification. According to the obtained value, the voltage for SMA is determined. With these operations, the fabric devices are tensed (or relaxed) and their shapes are changed to follow the digital data.

Firefry of freeware (Firefry, 2010) is often used to interlock Arduino with Grasshopper, while we have created the original middleware in order to enable application to 3D CAD systems other than Rhinoceros. Since the processing can be used in various protocols and a lot of plug-ins are prepared, it can be interlocked with various 3D CAD systems.

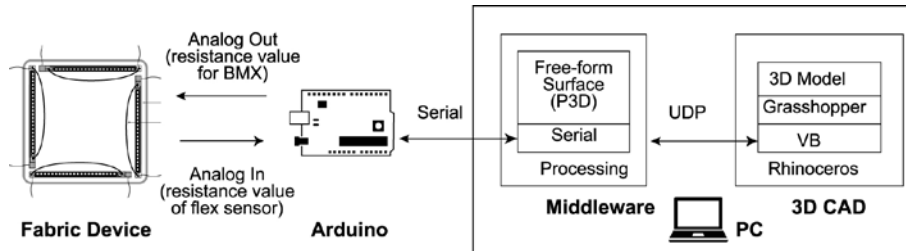


Figure 4. System configuration of SMAAD Surface.

3.4. HARDWARE

A fabric device (Figure 5) is a sheet of fabric produced by weaving white worsted yarns (3-strand No.6 thread). To each of the four sides, the flex sensor, which responds $10K\Omega$ in normal time and 30 to $40K\Omega$ when bent, is woven. At both ends of the flex sensor, the Ti-Ni series shape memory alloy (SMA) fiber (Toki corp. BMX 150, standard electric resistance $400\ \Omega/m$) is set in an arch line. The values of the flex sensor, representing the shape change of the profile lines, are sent to the microcontroller (Arduino Duemilanove) through a conductive yarn (Naslon stainless steel fiber, resistance: $11 \pm 10\% \Omega/m$). When electricity is given from the microcontroller, the SMA contracts and the PCB material of the flex sensor bows, so that the fabric shape changes. Controlling the extent of SMA contraction on the profile realizes various surface shapes. When 5V power supply is used, all SMAs complete their contraction in 5 to 10 seconds. Since conductive yarns are used, the wiring sections can be embedded in fabrics or the yarns can be embroidered to be combined with the fabrics.

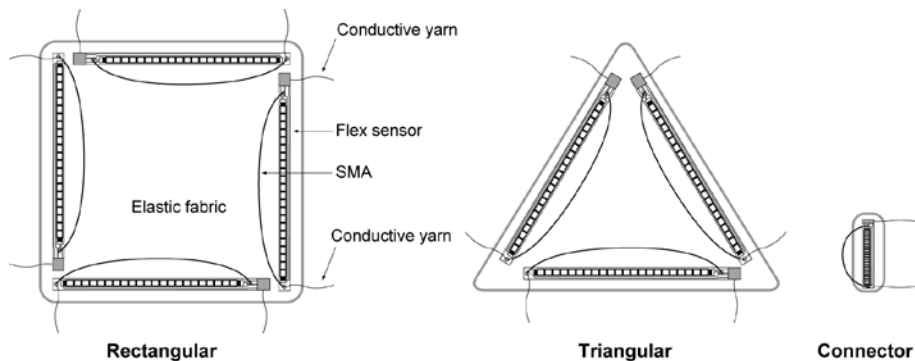


Figure 5. Modules and connectors.

4. Functions

4.1. DIRECT SURFACE MANIPULATION

With the feature, shape preservation, of fabric devices, direct shape modeling is provided. The direct operations to fabrics allow natural finger actions for both hands. Due to this, various interaction styles can be realized, from sensitive local operations such as pinching or pressing the fabric with fingers, to global operations such as crumpling the fabric into a ball, twisting, rolling or folding the fabric. Even after the direct operations, the SMA preserves the fabric shape as if soft wires are woven in the fabric. Therefore, designers can carry on the shape modeling as if they mold an expected object out of the fabric. The researches in recent years reveal that the TUI is more effective for perception and recognition of space than the GUI since the TUI allows natural manual operations (Kim et al, 2006). The functions to produce 3D digital data through natural manual operations are effective.

4.2. UNDO AND REDO

The surface shape data sent continuously from the flex sensor is saved as operation history and used for the operation replay. This allows the UNDO/REDO operations of the modeling. With this function, a new function to relieve the modeling process may also be realized.

4.3. MOTION DESIGN FOR KINETIC ARCHITECTURE

The operation history saving and replay are also available as the function to record and reproduce motion design, executed in the two steps below. In the first step, the direct operations sent from the flex sensor are recorded in a certain period of time. In the next step, the recorded motion is applied to SMA in the same period of time to reproduce the motion. This function will be used for the design environment of kinetic architecture such as Hyposurface (Ritter, 2006) or The Muscle Projects (Oosterhuis et al, 2008), which are attracting attention in recent years.

4.4 CREATIVE UI

In addition to the three suggestions in the former sections, various functions will be realized depending on designers' creativity. For example, stroking a smooth wall surface with this interface imports the shape into a CAD system. Combining this function with the algorithm to create surfaces according to the extent of bending, our system will function as a device for interactive algo-

rhythmic design.

5. Discussion

We offered designers this system and interviewed them to get the following comments. “Since the system preserves the fabric shape, I could model it through intuitive operations with my hands. This is effective to repeat trial and error and refine the shape.” “When some CAD data is input to change the shape of a fabric device, the whole device size becomes too large to deal with.” The former comment indicates the effectiveness of this system as an input method. This also shows the possibility of this system functioning as a new prototyping material to replace paper or styrofoam. The latter comment indicates necessity for improvement of this device. Since the fabric device we prototyped had only one inflection point and the shape is similar to a quadric free-form surface, a lot of fabric devices are necessary to represent a complex surface shape. To solve this issue, the SMA on the boundary lines are divided into segments and SMAs are arranged further on a fabric surface, so that a single fabric device can deal with a broader area.

6. Conclusion and future work

In this paper, we proposed SMAAD, the design technique to realize intuitive shape modeling with synchronizing a physical model and a 3D CAD system. The prototype system enabled direct design of organic free-form surface shape with using the fabric TUI. At present, we succeeded in connecting four fabric devices. In the future, if several dozens of the devices can be connected, it will be possible to actuate versatile shapes. This means that the SMAAD functions as a rapid prototyping system beyond design systems. Long time to wait for the output from the 3D printer will not be necessary anymore and immediate prototyping will be possible to grasp shapes in a moment.

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ARCHITECTURAL CREATIVITY IN COMMERCIALISED CYBERSPACE

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Abstract. This paper is written for architectural researchers, practitioners and educators who explore the potentials of networked, location-aware, rich-media computing. Augmented and networked environments open new possibilities in urban and architectural design. At the same time, their adoption by the mainstream is underpinned – and constrained – by commercial motivations. To be able to counter the consumerist interpretation of inhabitable augmented environments, the field of architecture needs to foster a critical discussion of cyberspace. In turn, architectural education needs to provide students with the knowledge necessary to adopt cyberspace for creative purposes. The purpose of this paper is to invite further discussion and experimentation in this area.

Keywords. Cyberspace, context-aware computing, locative media, ubiquitous computing, architectural creativity.

1. Introduction

This paper arose from a theoretical course on the ways in which digital technology influences architecture. This course, called *Production of Digital Space*, is taught at The University of Melbourne by one of the coauthors, Stanislav Roudavski. The paper was originally drafted by the other coauthor, Sonya Parton, as an assessed essay for the course. Subsequently, the paper has been extended through additional research by the two authors. This additional work has included discourse analysis, informal interviews with the members of the local architectural community and questionnaire-based communications with

the designers of the examples. This research has revealed well-developed literature that is simultaneously richly suggestive and – as our literature analysis confirms – unclaimed in the architectural discourse. However, the authors admit to the speculative nature of the paper and accept that it needs to be seen as a beginning of a more sustained engagement with the theme. At the same time, we propose that the paper can be useful in its present form because it introduces a new perspective by borrowing from well-substantiated knowledge in one field in order to enable the critical development of another. Such importing of knowledge, enabled by the discourse analysis and the reasoned consideration of possible implications is a well-established methodological device typical to cultural studies and critical theory – the disciplines that can elucidate social meanings of current technical developments. We reason that up to date, computer-aided design research – as represented, for example by the CAADRIA conference – has over-focused on technical concerns and hope that our paper can contribute to the discussion of what such concerns might mean as cultural phenomena.

The topic of this paper is motivated by its authors' interest in interactive and networked technologies and in their role in future architectural practice as well as in current architectural education. Stanislav Roudavski has a background in developing projects using such technologies including real-time navigable multiuser virtual environments and has participated in prototyping of speculative mobile applications and possible future-museum environments. For both authors, it is clear that such technologies will be increasingly used in architectural design. And more, that they change the very definition of architecture. In response, such environments ought to be taught to future architects. However, this challenge is nontrivial given the current scarcity of practical implementations emanating from the architectural profession and – especially – the lack of an established theoretical treatment of such technologies in architecture.

In the 1990s, the discussion on cyberspace – triggered among others by Benedikt's (1991) influential collection – was very prominent in the architectural discourse (e.g., cf. Castells, 1991; Mitchell, 1995 and many others). At that time, inhabitable cyberspace was not broadly accessible and much of the discussion focused on its possible functional performance: the effects on cognition and navigation, the ability to form places, its capacities to sustain office work, education or social activities. Our analysis of current literature demonstrates that in architectural discourse, including computer-aided design forums, the discussion on cyberspace as an overarching concept has subsided. However, much of the existing work on networked technologies in the field of architecture was completed before the emergence of broadly popular massive

multi-player games, social networks, location-aware smartphones or RFID and QR tags. Consequently, we suggest that architectural research should return to this concept and study its actual performance and implications.

To understand what such technologies might mean for architecture and – therefore – to establish how to structure the discussion about their meanings in an educational setting, this paper asks the following questions:

- What critical issues relevant to the architectural discourse can be highlighted by the historical trends in the utilization of networked technologies?
- How are ubiquitous technologies currently utilized in architecture?
- How are ubiquitous technologies currently taught to architects?

These questions set the scope of this paper and establish criteria for validity. This scope includes an overview of a historical progression used as a context to contemporary examples and as a foundation for a projection into the future. The validity of the findings can then be judged not by their quality as true statements but by their ability to provoke exploration, research, critical reappraisal and creative appropriation in educational settings.

2. From ad-hoc creativity to standardisation and trivialisation

The contents of this section are derived from the analysis of the discourse on the relationship between cyberspace and architectural creativity. A complete overview is beyond the scope of this paper. Instead, this section briefly outlines a particular area of concern that has emerged from the overarching survey. These concerns focus on the effects of commercialisation.

Early history of cyberspace can be discussed as the history of the Internet. In the early 1980s, prior to the establishment of the global system existing today, the Internet was a series of disjointed and enclosed networks, primarily used by military and academic institutions. The Internet's original creators and users aimed for a networked environment which was open-source, democratic and self-regulating (Moschovitis, 1999, ch. 4). Funding was provided by public institutions rather than private entities (Meikle, 2002, p. 13). In addition to the absence of direct governmental control, there was no commercial dependency. This situation was valued and at the time cyber-rights lobby groups called for the governments not to claim sovereignty over portions of cyberspace (Meikle, 2002, p. 33).

In 1988, the internet was opened to privately run service providers. By the early 1990s independent commercial networks began to grow. The subsequent development of the World Wide Web saw the Internet grow dramatically (Moschovitis, 1999, ch. 5). This increase in users resulted in interest

from commercial entities looking for profit.

Today's cyberspace is different from the visions of its early creators. The original democratic intentions are waning. Already in 1999, Lessig (pp. 6, 7) argued that "[c]yberspace, left to itself will not fulfil the initial promise of freedom. Left to itself, cyberspace will become the perfect tool of control." Currently, the Internet still relies on self-regulation and is lacking a general governing apparatus. The lack of governance protecting the common good led to the Internet becoming a "tool of control" in a different way – through privatisation and commercialisation (Hunter, 2003, pp. 443–446).

Cyberspace was appreciated as an environment intimately intertwined with the physical world even in the days before the recent massive advances in ubiquitous computing (Hunter, 2003). It has the capacity to modify perception and alter people's engagements with the world. Acting as a lens or a filter, it can exert control over people's access to information and over their experiences. If cyberspace is a lens, then interfaces to cyberspace act as translators of the content within. These translators have the potential to filter and direct access to this content (Shapiro, 1988).

These filters (software, hardware, server and hosting providers, UI elements, etc.) are typically designed, built and maintained by private companies motivated primarily by financial considerations. These agents can and do distort the operation of their tools for their own benefit.¹ Application of these constraints subverts the democratic nature of cyberspace (Lessig, 1999) and most of the time this subversion is not obvious. At the same time, the illusory freedom of navigation and selection is typically maintained, making educated choices and exercise of critical judgement more difficult (cf. Gleason and Friedman, 2004, pp. 306, 307).

Most of this manipulation is completely legal and frequently praised for being financially and technically innovative. For example, Google's behaviour routinely contradicts its own mission statement "to organize the world's information and make it universally accessible and useful" (as cited in Iyer and Davenport, 2008). Google succeeds by providing services that attract many users and coupling them with an effective advertising system. It seeks to spread its influence and impose perceptions and behaviours that bring it benefits. Google is involved in blogging, radio and television advertising, online payments, social networks, mobile phone operating systems, and many more information domains. It uses many tools that it did not develop but now controls: Picasa for photo management; YouTube for online videos; Double-Click for web ads; Keyhole for satellite photos (now Google Earth); Urchin for web analytics (now Google Analytics). It pays hardware manufacturers to make Google the default search engine on their new machines. It can record

users' search history and customise search results. For payment, it promotes web pages, companies and advertisements. As a result, it is able to influence the worldview and behaviour of a very large number of people (on these and other Google's tactics, see Vise, 2006). As a commercial organisation it uses this influence to gain profit. Abelson et al (2008) argue that search engines are brokers rather than providers of information. They do not "supply the undisputed truth, nor even to judge the accuracy of material that others provide. Search engines connect willing producers of information to willing consumers. [...] To stay in business, a broker just has to give most people what they want, consistently over time." Even without tempering this commercial template leads to trivialisation.

A telling example of another common phenomenon is the hugely popular social networking site Facebook. A recent review by Zadie Smith (2010) provides a convincing critique of its effects. When an individual is cast into the standardised shape such a social networking system provides, his or her personality is reduced to a set number of basic characteristics. Even apart from commercial ambitions that interpret people according to their "capacity to buy, attached to a few personal, irrelevant photos" (Smith, 2010, p. 59), the schemes that define such characteristics are often characterized by a haphazard, accidental quality because they were developed recently and locked into the current form quickly before they could mature (Lanier, 2010). Lanier argues that 2.0 environments constrain creativity by spreading commercialisation, enforcing standardization, constraining individual expression, obscuring authorship and presenting creative outcomes outside of their original contexts, dissociated from the original intentions of their authors.

To us as common users or as representatives of the architectural field these conclusions were counter-intuitive. The in-depth discussion of this material in the *Production of Digital Space* course and the informal interviews with members of the local pedagogical community confirmed that the awareness of the effects of commercialisation on cyberspace were rarely considered or discussed despite the increasing integration of networked technologies into urban and architectural environments and practices. From this we conclude that further exploration of this topic – aimed at increasing critical awareness as well as practical recommendations – will be beneficial to the architectural discourse and pedagogy.

To move the discussion from the general overview of cyberspace towards architectural concerns, the next section refers to several examples of current practice.

4. Examples of architectural design in the context of commercialised cyberspace

Until recently, cyberspace existed as an experientially distinct realm. Users took a conscious choice to access it via dedicated terminals. This has recently begun changing. The concepts of augmented reality, ubiquitous computing or locative media embed connections, content and intelligence into physical environments. These technologies allow multiple, in principle infinite, layers of information to coexist in physical locations that previously could hold a limited number of physical objects or interpretations. Such hybrid environments can be flexible and dynamic. The information they link to can be updated or even compiled on demand. Such environments can be more informative, efficient and adaptable than purely physical settings. However, this promise can only be fulfilled if the additional information and the meanings it supports are of quality and depth. In practice, this is not often the case. As an extension of the established networked practices discussed above, such environments are typically built by commercial entities and focus on consumerism at the expense of all other alternatives.

A current example of this technology is the Layar² development environments for mobile devices. Using built-in GPS and compass, the application overlays information on top of physical-world images as seen by the phone's camera. This application is able to recognise elements of physical environments and associate them with relevant content with the images that it recognises. According to the promotional literature and the existing client base, the primary target group for this environment are businesses that wish to advertise their products or services. This and multiple other similar applications are characteristic examples of technological lenses that re-interpret urban environments as predominantly commercial. Through virtual augmentation, they modify the meaning of the city and its architecture. Such applications can be built for non-commercial purposes, for example for finding and identifying historical (Liu and Lee, 2009) or unrealised³ buildings. However, even in these cases architectural designers have to rely on meaning structures, interfaces and technologies provided by others and developed with standardising, commercial purposes in mind. The need to work with architectural environments via specific structures created and maintained by others establishes new constraints for architectural design and questions architects' capability to design in direct response to local conditions. The implications are far from obvious but – again in reference to our literature survey – further study and practical experimentation, especially when educating new designers, is necessary for the development of critical awareness and suitable creative strategies.

Augmentation also begins to occur on a building scale. For example, the

N Building in Tokyo by Terradesign⁴ and Qosmo⁵ utilises a concept similar to the smartphone applications discussed above. However, in the case of the N Building a giant QR code is used as the only decoration for the façade. The N Building is a shopping mall and the QR code can serve as a link to information about the activities in the building. A user can scan the code and obtain information about the shops, gain an ability to make reservations or download coupons. Additionally, users can see other people attending the building as well as their comments made online. Each user can also contribute comments that become associated with the building and accessible to others. The use of QR code as façade decoration is not a technical necessity. As the Layar applications demonstrate, image recognition software can provide such an association without the use of standardised tags. However, it highlights a growing trend to transfer a significant portion of architectural meaning into the cyber portion of the hybrid environment. N Building authors envisage that in the future building facades might disappear to give way to flexible, dynamic content. However, if the types of content to replace the physical architecture will include nothing more but social small talk and commercial information, the environment will become impoverished. In N Building, designers took a deliberate step to pass the responsibility for meaning creation to clients and users of the building. They provided the cyber extension using standard, commercially available hardware and were constrained by its affordances. If this example is to become common practice, does it constitute the abandonment of expertise and trivialisation of an architectural endeavour? If the result of this process is a collaborative creation that involves users of the building who generate the relevant content, should the design include the mechanisms for the curation of virtual information?

Writing in 2006, Edler and Edler observe that the technology for the construction of media facades is becoming more accessible but that their utilisation to date commonly takes the form of electronic advertisement boards disconnected from the local context (Edler and Edler, 2006, p. 181). The standardised, rectilinear forms of such boards are determined by the screen manufacturers and do not respond to the site-specific needs. Similarly, the content they broadcast is typically produced as generic advertisements with no intentional relationships with the host building or the surrounding context. Frequently, when a building acquires a media façade, the architects involved in the project lose control. With this loss, the relationships within their care – for example the relationship between the interior and exterior between the building and the site – become neglected. “[A]rchitects have to start not only to tolerate media surfaces on their buildings but [...] claim them as a powerful opportunity to extend their influence and responsibility in the design process.”

(Edler and Edler, 2006, p. 182) Projects from *realitis:united*, such as BIX⁶ or SPOTS,⁷ attempt to address this problem and create designs integrating media and architecture. Among the outcomes of *realitis:united*'s experiences are the examples of design processes that can lead to the generation of quality content for media facades. For example, in their SPOT project, the practice collaborated with other interested parties to curate a balanced portfolio of such content. Their conclusion was that the conventional display of commercial messages was insufficient to satisfy the client's aspirations for self-promotion simultaneously with the public's desire for spaces that represent and support the current concerns of society. The bias towards a completely non-commercial selection in the SPOTS project was also unsuitable and the team created a pattern that divided week days between artistic exhibitions and commercial advertising. This experience is unusual in traditional architectural design and its success emphasises that architecture practice needs to develop new protocols for the designing of interactive (and networked) systems. These protocols need to take into account the technical and conceptual capabilities of such systems within the framework of architectural design. As these systems are intrinsically dynamic, their design needs to be supported by specific tools that are able to simulate their performance and make it easily adjustable. Because virtual extensions link architecture with tools and systems developed and controlled by others, these new design protocols need to consider who and how can produce appropriate, high quality and/or critical content that can be harmoniously integrated with physical structures.

Currently, such protocols, tools and methods are not readily available in the form of established workflows. Consequently, further experimentation based on a critical understanding of the contemporary situation and involving cross-disciplinary expertise is necessary for further progress.

5. Preliminary conclusions

New media and networked environments create new challenges and opportunities for architecture, city planning and urban studies. These opportunities can only be successfully explored if these disciplines succeed in developing a critical awareness of their effects. Such awareness is currently lacking. (Foth and Sanders, 2008, p. 77)

This gap in existing knowledge should be a cause for concern. Lanier (2010) suggests that "digital creativity eludes flat places" and warns about the dangers of "flat information networks that suppress local contexts in favor of global ones." The discussion presented in this paper suggests that such effects of standardisation begin penetrating the domain of architecture. Indeed, Graham (2005) reports a growing recognition that "corporations are increas-

ingly attempting to 'package' electronic spaces for the purposes of electronic consumption in ways that closely relate to, and increasingly actually join with, the wider commodification of urban space." Taking into account the historical trend towards commercialisation of networked environments discussed above, will architectural and urban projects succumb to commercial saturation, commodification, standardisation and "flattening" that will by far surpass the similar processes in physical environments?

To be able to understand the performance of an augmented environment and appraise the available alternatives, architects need to understand the implicated technologies, motivations they embody and the affordances they offer for designing. Understanding and operating such technologies is a complex challenge that extends well beyond the confines of conventional architectural education. Greater collaboration with adjacent disciplines is therefore increasingly necessary. This collaboration needs to be underpinned by the relevant domain knowledge catered for by specific offerings within architectural education. The relevant educational content should constitute critical appraisal of the theory and practice of augmented environments, potentially leading to the emergence of new specialisations within the architectural profession but also informing all students about the relevant issues.

Endnotes

1. E.g., cf. recent EU's antitrust probe into alleged Google's self-serving manipulation of search results. <http://www.bbc.co.uk/news/technology-11876443>
2. <http://www.layar.com>
3. <http://phantomcity.org/>, <http://www.rietveldjaar.nl/>
4. <http://www.terradesign.com>
5. <http://qosmo.jp/> Information on N Building and authors' aspirations was kindly provided by Alexander Reeder of Qosomo in a personal communication.
6. <http://realities-united.de/#PROJECT,69,1>
7. <http://www.realities-united.de/#PROJECT,81,1>

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A WORK SERVICE MODEL OF THE UBIQUITOUS OFFICE

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Abstract. In recent years, office environments adopt ubiquitous computing with a focus on collaboration and mobile communication to promote real-time enterprises. Within this context, this study deals with a significant issue on the ubiquitous office environments by understanding human behaviors and works. We propose a ubiquitous office model considering the correlation between ubiquitous computing technologies and work services in the office. Two attributes are focused, collaboration and mobility, as identifier for categorizing the work types. The classic types of work services have variations in the amount of communication and the proportion of working outside of the office. The proposed work service model includes territorial and non-territorial services for the ubiquitous office to enable workers in and out of the office to interact with each other. The findings in this paper would be a theoretical basis for embodying the intelligent office which supports office works efficiently and effectively.

Keywords. Ubiquitous office; work service model; ubiquitous computing; context awareness; collaboration.

1. Introduction

The development of computers and the Internet has changed human life styles as well as societal and economic activities. Recently, for the real-time enterprises, the office environments deal with ubiquitous computing with a focus on collaboration and mobile communication. By understanding human behav-

iors and works, this study proposes a ubiquitous office model through considering the correlations between the ubiquitous computing technologies and work services in the office. We adopted the work context from Alternative Workspace Strategies (AWS) proposed by Gilleard and Rees (1998), which provides a unique context in the ubiquitous office. The ubiquitous office is not what is operated passively by inhabitants but an active information-oriented office that can predict the situation and working patterns of inhabitants. This paper emphasizes the way of making computers understand the situation and the work patterns in an office environment.

This paper consists of three parts: 1) description of the research background with a focus on the concept of the news office and the ubiquitous office; 2) a survey of enabling technologies and their applications in the field of the new office; and 3) the proposition of the service processes of the ubiquitous office in the work service model.

2. Background

2.1. THE NEW OFFICE

The *new office* is defined as all offices which are opposed to the traditional office, and extended to include a shared space which has no time and place limitations. Duffy (1997) described that the traditional office has routine processes which include many individual tasks isolated from the others. On the contrary, the new office supports creative knowledge work which generates interactive workflow. Also, the new office can be distributed and connected for communication through the network. Our daily working time can be expanded to be flexible in mobility. Ubiquitous and mobile technologies empower the creative knowledge work, which ranges from individual to group-oriented.

Gilleard and Rees (1998) described AWS including workplace redesign, on-site/on-premises strategies, and off-site/off-premises strategies as shown in Table 1. Especially, the virtual office reflects the concept of ubiquitous computing (Weiser, 1991). With the development of Mixed Reality (MR), the horizontal and vertical surfaces of the office were augmented for the future visualization (Raskar et al, 1998). The AWS instructs us how to predict and control the work context. Also, the AWS presents similar characteristics to those of the ubiquitous office, mobility for the non-territorial feature and ubiquity for the territorial feature.

Table 1. Alternative workplace strategies (Gilleard and Rees, 1998)

Workplace redesign	Flexible work schedules	That maximize use of office space
	Modified office standards	To improve productivity and efficiency, and support organizational objectives, such as establishing universal standards.
On-site/ on-premises strategies	Free address	Workspace shared on a first-come, first-served basis usually in a large open space with many workstations.
	Hoteling	Workspace that is reserved on a first call basis and not dedicated to any specific worker beyond a specified occupation time.
	Group address	Designated group or team work space for specified period of time
	Share space	Two or more employees sharing a single, assigned workspace and work tools, either simultaneous or on different shifts/schedules.
	Project team environments	Flexible work areas designed to support work teams as they expand and shrink
	Activity settings	Providing a variety of work settings to fit diverse individual or group activities such as a lounge area, desk work area, conference area, etc.
Off-site/ off-premises strategies	Telecommuting (Home-based)	Combination of home-based and office workspace linked by technology, with employees utilizing their office workspace one or more days a week.
	Satellite officing	Office centers providing technology and administrative support located near employee residences and used full-time by employees living closest to satellite site.
	Remote telecenters	Office centers providing technology and administrative support, located near customers and staffed by employees dedicated to that site or splitting their time between that location and another.
	Virtual officing	Employees have freedom to office anywhere -home, car, hotel, etc. -through the use of portable technology.

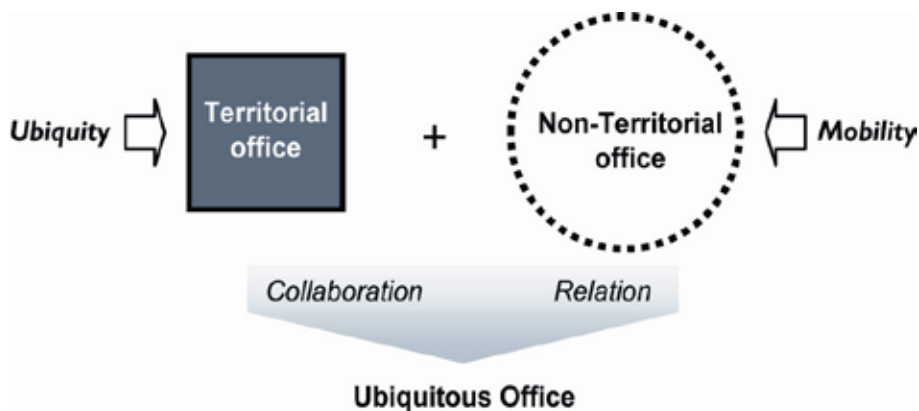
2.2. UBIQUITOUS OFFICE

Weiser (1991) described the ubiquitous office as a one room that has hundreds of computers connected to each other through cables and a network. There is a growing interest for the new office space that combines physical and electronic space through the ubiquitous technology.

The ubiquitous office is also defined as an environment where user can utilize computing technologies intuitively without recognizing the computers (Lee and Lee, 2004). In other words, for making the more comfortable working environment within an office, a variety of embedded computers make inferences, interpret and respond to the situation through the perception on the context of workers, which keeps the effective and comfortable environment. Also, the ubiquitous office integrates the mobile environments where mobile devices enable the users to be connected to other devices and col-

leagues distributed at any time (Schilit et al, 1994; Gellersen et al, 2002; Hohl et al, 2002; Henricksen, 2002).

The ubiquitous office contains sensors and devices that adopt various location-aware technologies such as GPS and WPS. The context awareness can be achieved through the use of the devices and sensors, thus producing customized and appropriate work services. The features of the ubiquitous office can be divided into two categories: One is the territorial attribute that provides intelligent services through the understanding of the context of the works and users; the other is the non-territorial attribute that works in the mobile environment. Figure 1 shows the characteristics of the ubiquitous office.



3. Previous relevant work

This section critically reviewed the previous relevant efforts in advancing the new office, although some of them did not deem their cases as new office. The section derives certain important characteristics that the new office should possess.

3.1. ON-SITE/ON-PREMISES STRATEGIES

3.1.1. IBM (UK)

Since 1989, IBM has tried to find out a desirable workplace type for sales staffs and realized that keeping the personal desk is not efficient. More important thing is to provide a workplace where the sales workers can meet customers and access to the technology supports. Well-equipped open breakout spaces

to meet with colleagues are more important than reserving individual private spaces for persons who sometimes drop by (Duffy and Powell, 1997).

3.1.2. ACCENTURE

Accenture has been operating the 'hoteling' strategy for the mobile office. This office accommodates 800 staffs in 168 seats and allots 3-5 consultants to one workspace. Since there is no executive workspace, the concept of the horizontal office is realized. By focusing on public and meeting spaces, the department of supports, each consulting team consisting of 4 persons, assists the work environment in the office (De Long, 2001).

3.1.3. DOWA HOLDINGS

DOWA Holdings is one of the successful cases among companies in Japan which adopt the 'free address' strategy. Contrary to the traditional offices, Yosikawa Hirokazu, CEO of DOWA Holdings, broke the physical walls among workers when renovated the headquarters. On the 'free address' strategy adopting wall-breaking, workers should keep their office stuffs in their private cabinets and pick their seats when they start to work. The working pattern enables workers to share their information and interact with each other (Hirokazu, 2007).

3.2. OFF-SITE/OFF-PREMISES STRATEGIES

3.2.1. NTT Group

NTT Group consisting of NTT Data, NTT Communications and NTT software established a home-based working system for their workers, which allows the workers, except sales staffs, to work at home one time in a week. Because of security problems, the group has prohibited the workers from using paper media and made them loan Sun-Client- install PCs from the group. That is, the group limits their employee's works due to the concerns of the information leak (Baek et al, 2009).

3.2.2. Interagency Telecommuting Pilot Project of GSA in USA

GSA (General Service Administration) implemented the pilot project from 1993 to 1996 and advised each administration to execute various types of working systems (telecommuting, telework centers etc.). GSA prescribed to implement the teleworking, outside of office, for more than one day in a month. The teleworking project in GSA established a telework center network

in the areas near Washington in the beginning of 90's (Jeong et al, 2007).

3.2.3. Cisco Mobile Office

Cisco is realizing the mobile office through UC (Unified Communication). UC is a system that integrates various communication means such as telephones, fax, e-mail and cellphones into a single platform, which enables continuous communication without being cut off. Especially, Cisco minimizes employees' business trips to abroad by installing 'telepresence', one of the technologies of UC, in their branches. Telepresence is an IT system to enable the face-to-face meeting through real-size videos (Cisco Public Information, 2008).

3.2.4. Samsung SDS

For the implementation of the mobile office, employees in Samsung SDS were given smart phones with Mobile desk program. The program that enables the employees to work at any place and time successfully reduces cost and increases productivity. Being connected to the office mail systems and mobile devices through a wireless network, workers can receive and respond to e-mails (Seon and Kim, 2010).

3.2.5. Seoul Metropolitan Rapid Transit Corp (SMRT)

The previous UTIMS (Urban Transit Infrastructure Management System) of SMRT (Seoul Metropolitan Rapid Transit Corp) shared all the information of 5, 6, 7 and 8 line trains with their branches in real-time, but maintained the facilities asynchronously when the repair was available. The mobile support system associated with computer technologies was established and responds to the civil complaints making relieving uncomfortable things at one-stop real-time, which increases the customers' satisfaction on the services (Bae et al, 2010).

4. Work service model

4.1. ENABLING TECHNOLOGIES

Various ubiquitous environments have been implemented by different technologies. Specifically, the technologies have been developed with a focus on the supports of the collaboration in office works. The support can be divided into two types: indoor office collaboration and outdoor office collaboration.

The technologies adopt the territorial attributes and devices of the

ubiquitous office when workers collaborate with team members. Most of tables and walls allow workers to interact with co-workers as shown in Figure 2. Wellner (1993) proposed 'Digital Desk' that provides electronic and actual documents simultaneously using a tablet and pen on a table and projected screen of the computer. iRoom of Stanford university (Borchers et al, 2003) was developed as an open meeting room including interactive walls and tables. The room has cameras, microphones, wireless LAN supports, and a variety of wireless buttons and other interaction devices. Also, Streitz (1999) coined the concept of Roomware and studied on the workplace of the future which was described in i-LAND. The space has Dynawall that can be used by several persons interactively, CommChair, a kind of chair, implemented in a computer and InteracTable is available for the interaction.



Figure 2. iRoom (left)(<http://ldt.stanford.edu>) and i-LAND (right)(Johanson et al, 2002)

Telepresence technologies allow workers who are far away from their offices to contact with their colleagues inside the office. The workers can feel like to be present in their offices together with their colleagues and have no difficulties in collaborating with them. Compared to the traditional 2D-based telepresence systems, more realistic 3D mapping techniques have emerged in the area of the collaboration.

The followings are the major technologies adoptable for workers who are working outside their offices. In order to support mobile workers who do their personal and collaborative work with colleagues in indoor offices, the advanced technologies and applications are being developed. The Active Badge Location System (Want et al, 1992) is to provide the location information on the workers who wear the badges through the network sensors. The location-based services have been significantly developed since long time ago. The ubiquitous vision of Victor Poznanski (2004) has the non-territorial attribute and emphasizes the mobility. Therefore, it proposes the nomadic access to the information and services needed for the mobile workers.

4.2. WORK SERVICE MODEL FOR THE UBIQUITOUS ENVIRONMENT

In order to propose a new office model for the future, we developed a work service model of the ubiquitous environment as illustrated in Figure 3. The model describes the processes of the work services. With a focus on the territorial aspects of the offices, we consider two types of attributes of the ubiquitous office for the work service model: one is the territorial office, and the other is the non-territorial office.

The processes of the territorial office are the left part in Figure 3. New values in the context captured by various sensors are perceived by the Office Agent, and then the information is delivered to the Context Interpreter for reasoning the situation through 5W1H. If collaboration is necessary, the Collaboration Provider is then conducted accordingly. If not, the Appliance Controller takes the information and executes the work service using the Office Appliance. On the other hand, those of the non-territorial office start from the location-based context awareness. For example, Location Based Services (LBSs) such as Wikitude and Layar offer the service by interpreting information sensed by GPS. The location information in work context is handled by the Mobile Application. The critical point in the process is the three kinds of relations to the information, thus the mobile process searches for users, objects, and place relations, which is computed by the Relation Provider. Context Awareness is captured by either sensors or mobile devices in the ambient media environment, where the territorial and non-territorial services can be integrated seamlessly in collaboration.

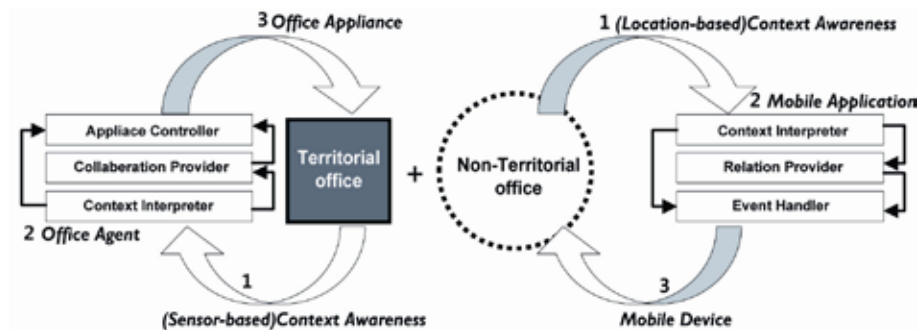


Figure 3. Work service model for the ubiquitous environment.

5. Conclusion

This study argued the ubiquitous office as the new office and investigated into the types of new offices and the background of the ubiquitous office through

the literature review. Also, the ubiquitous office was divided into two features. One is the territorial attribute that understands the context of the works and users and provides intelligent services. The other is the non-territorial attribute that can be applied for the mobile environment. Through the case study, this research identified what actual office works are, what work services are provided according to the degrees of the collaboration and mobility, how the ubiquitous office is adopted and what kinds of technologies are available for ubiquity and mobility.

Ultimately, this study proposed a work service model of the ubiquitous environment and presented the processes for the territorial and non-territorial offices in the ubiquitous environment respectively. More case studies, advanced technologies and investigation are needed for the future study in order to verify the proposed work service model. This study adopted a novel approach to the development of the work service model by integrating two attributes of the ubiquitous office. We plan to do research on the users' experiences and the ways to improve the ubiquitous office in more detail as a next step of the research.

Acknowledgements

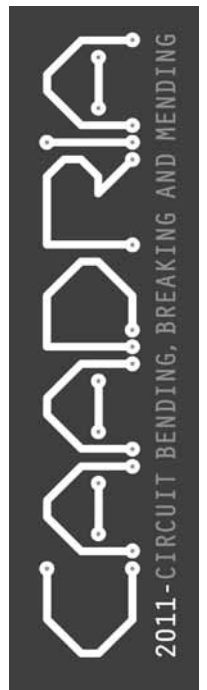
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DESIGN COGNITION



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37.	An ontology representing Roberto Burle Marx's landscape design solutions	389
	<i>Carlos V. Vaz, Gabriela Celani and José P. Duarte</i>	
38.	CAD software as customisation tools: Using FBS protocol coding scheme to understand the behaviour of mass customisers	399
	<i>Morteza Pourmohamadi, John S. Gero and Robert Saunders</i>	
39.	Rethinking concept design tools: High-level requirements for concept design tools	409
	<i>Volker Mueller and Ivanka Iordanova</i>	
40.	The polymorphic diagram: On mediating spatial thinking in architecture design	419
	<i>Qutaibah Hamadah</i>	
41.	Assessment of design tools for ideation	429
	<i>Edgar Pérez and Tomás Dorta</i>	

AN ONTOLOGY REPRESENTING ROBERTO BURLE MARX'S LANDSCAPE DESIGN SOLUTIONS

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Abstract. The objective of this undergoing research project is to propose a new approach to landscape design education, based on design cognition and computational design theories, such as patterns, shape grammars and parametric design. The system is based on an ontology that contains classes of design concepts and examples of their instances. This paper shows specifically the development of the ontology that will structure the whole system. The information necessary to understand each of the design concepts is represented by a schematic shape grammar rule. Each concept will be illustrated by a good example of application, extracted from the work of Brazilian landscape designer Roberto Burle Marx. A prototypical implementation of the system is being developed, with a hierarchical taxonomy of the concepts and examples.

Keywords. Ontology; landscape design education; Roberto Burle Marx; landscape architecture; pattern language.

1. Introduction

As Sweller (1994) has pointed out when a complex intellectual skill is recently acquired it can only be used by devoting considerable cognitive effort. The constant use of this new ability will contribute to turn it into an automatic cognitive process, decreasing mental effort. If that does not happen performing a problem-solving task using this new skill can be slow and may result in errors. Sometimes, this low cognitive performance may be identified in architecture students who are taking a design course for the first time. Usually, they have more difficulty processing new knowledge since they do not have

the background of a qualified professional. As a result, students often are not aware that a concept is being used to solve a design problem or do not give proper importance to a concept taught in class. They also can generate a lot of additional unnecessary problems by ordering data in an inadequate way while searching for a solution to the main problem. The design instructor has the task to teach an efficient method to organize the problem data and help select the correct variables and concepts to achieve a good design solution. This is not a simple task and one of the most common methods to help students overcome their difficulties is using design references.

Design references are solutions developed by an experienced architect that are used as examples of good design approaches. The problem of using references to teach is that novice students are not always able to make an abstraction and understand the general concept behind the specific solution. On the other hand, when an abstract concept is presented to them, they have difficulties in properly applying it to a specific situation, and need an advisor to help them. Instructors hardly have enough time to assist all students and, consequently, design errors are found only in later design stages. One way of avoiding this type of problem would be to develop a tool that can be used to help teaching design concepts to students in an organized and systematized way, relating such concepts to different design solutions (instances).

The goal of this research is to develop a system based on an ontology that can show design concepts to students in an organized way. The system will also show instances of each concept through design examples. Two main questions had to be answered before implementing the system. Firstly, what is the best way to organize the design knowledge? And secondly, what is the best way to present it to the user? The first question is directly related with two steps that need to be taken in the development of an ontology - defining classes and arranging the classes in a taxonomic hierarchy (Noy and McGuinness, 2000). The second question is related to how knowledge should be presented in the system to achieve efficiency during the learning process.

The first prototype contains the necessary knowledge to guide students during the design process to develop a landscape project. The designs selected as references - instances - are the gardens planned by Roberto Burle Marx. Burle Marx generally is acknowledged as the most famous Brazilian modern artist, who has influenced different generations of landscape designers. The design concepts were extracted from Burle Marx's projects and then organized in a series of patterns, following the same logic of Christopher Alexander's pattern language. As will be seen, the pattern structure and format were adapted to be used by students in the classroom.

2. How to organize knowledge? Progressive differentiation of intelligence

The structure of a system developed to help teaching design should have characteristics that enable a proper presentation of information to a student. The design knowledge represented in the system needs to be clearly hierarchically organized enabling students to understand the relation between different design concepts. There are some theories that deal with the way knowledge should be presented to increase learning performance. One of those theories is called progressive differentiation of intelligence.

According to Ausubel (2003), when a subject is taught according to the progressive differentiation principle, general concepts are presented to the students in an initial stage. That is to say, in your first pass through the material, you would teach the “big” ideas (the highest ones in the hierarchy). Subsequently, more specific concepts are presented to the students until the subject is completely detailed. This approach to teaching has many similarities to the natural cognitive acquisition process and content sophistication. Furthermore, it also corresponds to the way knowledge is represented, organized and stored in the human mind. Figure 1 - Graph A, shows how knowledge is structured according to the ideas of Ausubel (2003).

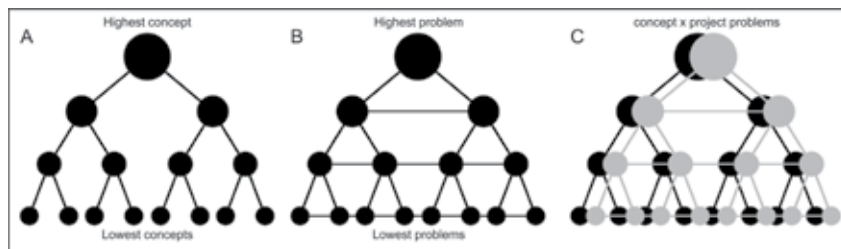


Figure 1. (A) Progressive differentiation graph. (B) Problem solving graph. (C) Progressive differentiation graph x Problem solving graph.

This knowledge representation can be considered similar to the structure of design problem-solving process. The search for a solution to a problem starts by presenting “big” ideas at the beginning of the process. The problem is progressively differentiated into specific and less complex problems that are solved by applying specific design concepts. However, the connections between problems in a design do not happen only from general to specific problems. There are also connections between problems that are on the same hierarchical level (Figure 1 - Graph B). A similar type of structure can be found in Christopher Alexander’s concept of pattern language.

Alexander’s Pattern Language is formed by a series of knowledge units called patterns. Each pattern has the necessary knowledge to solve a specific

design problem in the architecture domain - a problem which occurs over and over again in our environment. A pattern shows the essence of the solution to this problem in an abstract way, so that it can be applied to different concrete contexts. In Alexander's book, all the patterns are presented in a similar format, containing:

- An image showing a pattern instance;
- An introductory paragraph showing how this pattern helps to complement other patterns;
- One or two lines of text to introduce the problem;
- The body of the problem with empiric knowledge and examples;
- The solution in boldface with instructions on how to solve the problem;
- A diagram that represents the solution.

In "A pattern language: towns, buildings, construction" (Alexander, 1977) there is a set of 253 patterns organized in ascending numerical order. The patterns that have lower numbers are used to solve urban problems while patterns that have higher numbers are used to solve buildings and construction problems. Each pattern has connections that indicate its relationship to other patterns and to the language as a whole. The net that is structured by the connections between each pattern can be seen as the only organizational structure present in Alexander's language.

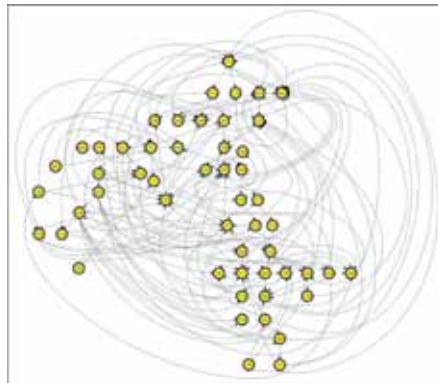


Figure 2. Graph constructed from Alexander's landscape patterns.

Nevertheless, in a pattern language the patterns are also organized in a hierarchical structure that helps the reader to find the pattern required to solve a specific problem faster. For instance, the pattern *Access to Water* (25) belongs to *Character of a local environment* super class. In turn, *Character of a Local Environment* super class is a sub class of *Towns*, and *Towns* is a sub class of the whole Pattern Language. This Scheme is illustrated in figure 3, graph A.

This hierarchical structure developed by Alexander will be used as a model for the part of our system that organizes the concepts. A second part of the system will contain examples and will be connected to the first part.

2.1. SYSTEM STRUCTURE SOLUTION

Certain landscape design publications serve as reference books that summarize and systematize knowledge. The knowledge is arranged in units that have information (sections, chapters, items and sub-items), rules and instances to solve one or more problems. The reader can search for specific information using its table of contents and does not need to read it from the beginning to the end, following a linear reading sequence. The book structure is developed by the author who is responsible to decide how to organize knowledge and information; some are more systematic and other ones are more informal. Compared to them, Alexander's book is much more systematized.

In this research phase, three landscape design handbooks were chosen to be analyzed in addition to Alexander's pattern language manual. Schemes were elaborated from the content tables to show how the information is organized in each handbook. Figure 3 shows the schemes.

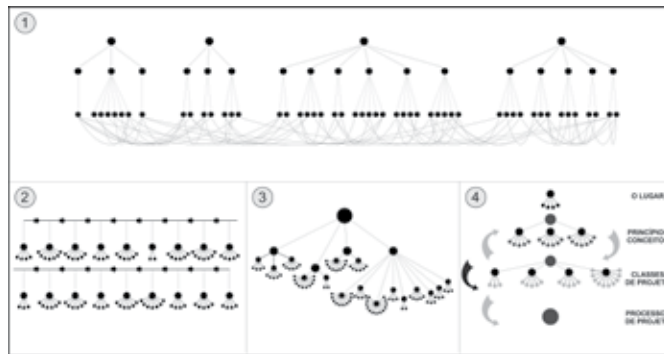


Figure 3. Schemes constructed from Alexander's *A Pattern Language* book (1) and three landscape handbooks (2-4).

The first scheme was developed from the *A Pattern Language* structure. Alexander's scheme differs considerably from all the other examples due to the cross links between concepts in different categories. The second scheme was elaborated from Simond's book (Simond, 1997), *Landscape Architecture: a manual of site planning and design*. This landscape design handbook was specifically planned to introduce the basic design concepts required to develop good design solutions, for instance; a square, a park or a house. The book chapters are organized in topics as circulation, structures and housing. It

presents a clear organization of design concepts, but not of design instances. Images of random projects are provided on pages separating chapters.

The third book studied was *The landscape of men* written by Geoffrey and Susan Jellicoe (1975). The book presents a historic approach to landscape design and uses sets of projects from different historic periods to show how the human being has been interfering with the natural landscape. The design concepts are implicit in the text and in the projects, but the design classification allows the reader to look for information in specific parts of the book. For instance, if the reader wants to learn about English landscape design, the book has a section that only contains projects designed according to this school. However, if the reader wants to know what are the concepts and principles used by an English designer to solve circulation problems in a garden he has to figure it out from the reading of the text.

The last and fourth scheme was developed from *The poetic of gardens* (Moore, Mitchell and Turnbull, 1995) table of contents. In this book the same importance is assigned to both concepts and examples. The first chapter shows the necessity to understand *The genius Loci* and collect correct information to assign suitable values to design variables. This is an important design phase because the designer should understand the spirit of the place to select the most appropriate design solution pattern for the current context. If a designer does not know how to read the place, s/he probably will have difficulties in achieving a good solution.

The second chapter introduces the main design concepts and components that a designer should know to develop a good design solution. The designer will apply this knowledge to the problem identified in the previous phase. As in Simond's book, this chapter is divided in items and each item has a family of concepts (irrigating and draining, lighting, warming and cooling, etc.). The concepts are presented in text format and some schematic drawings help the reader to understand the design principles presented in the chapter.

In the third chapter, four different design classes are defined – collection, pilgrimage, symmetry and scenario. Each class contains a set of gardens that represent good design solutions. For each garden there is a clear and objective description following the concepts presented in the second chapter. Consequently, there is a clear relation between concepts and instances.

The last chapter contains five fictional dialogues between the designers who developed the gardens described in the previous chapter. Each dialogue is a discussion illustrating the search for a solution to a design problem that a designer would have to actually solve. In these discussions designers from the past use concepts they used in the solution of their design problems to solve contemporary design problems. The point of these dialogues is to show how

old concepts can be used to solve contemporary problems.

The schemes inferred from the books permitted the construction of the system herein described. This model uses features of Alexander's pattern language to organize concepts and features of *The poetic of gardens* to classify design instances. The poetics of gardens was used as reference to build the model because it has a clear organization of design concepts, but also of projects used to illustrate their application. The other two books (*Landscape Architecture: a manual of site planning and design* and *The landscape of men*) do not have the organization used in *The Poetics of Garden* to relate design concepts to instances. The scheme of the proposed system's model is shown in figure 4.

In the scheme, the super class **DC** (design concepts) has four different sub classes where all patterns are organized as shown on the left side of the figure. The patterns have connections with other patterns on the same hierarchical level; as a result, it creates a net similar to the one implied in Alexander's language. On the other side of the diagram **PR** (projects) super class has two subclasses, **PP** (past projects) and **FP** (future projects). Each of these two classes has 4 subclasses - **SC** (scenarios), **PI** (pilgrimage), **CO** (collection) and **SI** (symmetry). These classes contain designs from the past (**PP**) and the future (**PF**), and have direct connections to the concepts classes on the other side of the diagram.

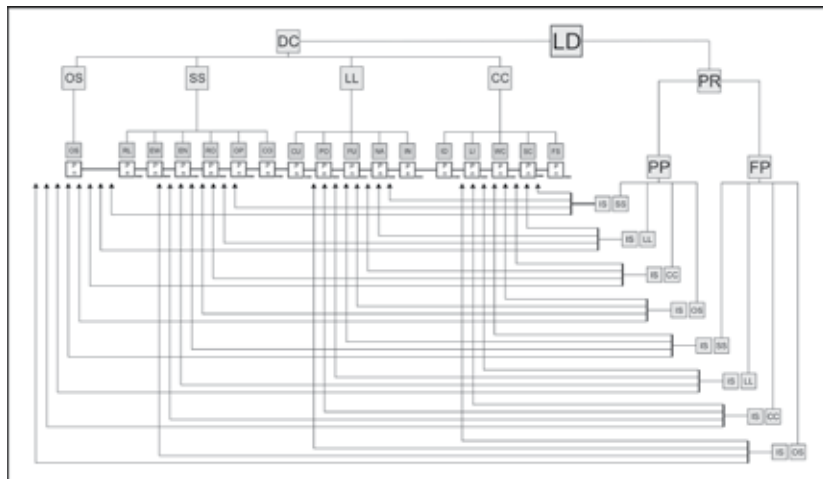


Figure 4. System class hierarchy.

The projects of the past in our model are the gardens developed by Roberto Burle Marx. Design concepts are extracted from these designs and organized according to the classification defined for the concept classes. The system will

allow students to employ the concepts used by Burle Marx and compare their solutions – future projects - to the solutions developed by an expert.

3. Cognitive load - what is the best way to present knowledge to the user?

After defining the landscape design teaching system model it is necessary to find a proper way to format information and set it up. In the same manner as progressive differentiation helped to create a hierarchy of concepts and design solutions, cognitive load can assist finding the correct approach to present information to students.

In 1956, a research study conducted by George Miller showed that the human cognitive system can only process 7 ± 2 digits simultaneously. If the number of elements is exceeded, reasoning and learning are jeopardized. Miller's work is the beginning of 25 years of research which resulted in the body of principles that underlies the cognitive load theory.

According to Clark, Nguyen and Sweller (2006) some activities have low cognitive load whereas others have high cognitive load. An example of an activity that has low cognitive load is to learn a language vocabulary. On the other hand, putting words together to create a sentence with this new vocabulary is an activity that has high cognitive load. In activities that have high cognitive load it is important to provide the students with a proper learning environment *to increase efficiency in the use of mental resources*.

Patterns in Alexander's language, as discussed above, always have the same format to present recurrent design problems, concepts, and solutions. However, even though patterns share the same structure, it is very difficult to use them because the amount of information that is necessary to manipulate. Besides, the way in which they can be used is not completely clear and systematic. This difficulty increases when it is necessary to work with different patterns together. Also, as it was mentioned, each pattern has more than one connection to other patterns and to solve a complex design problem it might be necessary to use several patterns. In these circumstances, the amount of information that is necessary to deal with will rapidly lead to cognitive overload. As our goal is to find a system to assist students in design learning, it should present only the information fundamental to clarify a given design concept. The student needs to understand the essential rules to apply a concept. But, what is the best way to represent rules?

Shape grammars are a type of production system that it is capable of generating shape compositions (Stiny and Gips, 1978). Each grammar has a shape vocabulary and a set of production rules that can be applied to generate designs. This type of formalism has been used to study existing design languages and to create new languages. In the first case, shape rules must be

well defined or the grammar will not be capable to generate design solutions similar to the existing language. In the case of new languages, rules may be more flexible to allow shape emergence, that is, after applying a rule an unexpected shape can emerge from the composition. The rules that will be used in our system do not need to be as restrictive as the grammar that describes a language. They need to show only the information and parameters that are essential to apply a concept. This type of rule is also known as schema. The use of shape grammars rules will provide an environment where the students do not need to understand concept rules by reading words, but by looking at shapes. The use of shape grammars to encode the rules for formalizing design patterns, that is, to instantiate design concepts, has also been proposed by Beirão et al (2008).

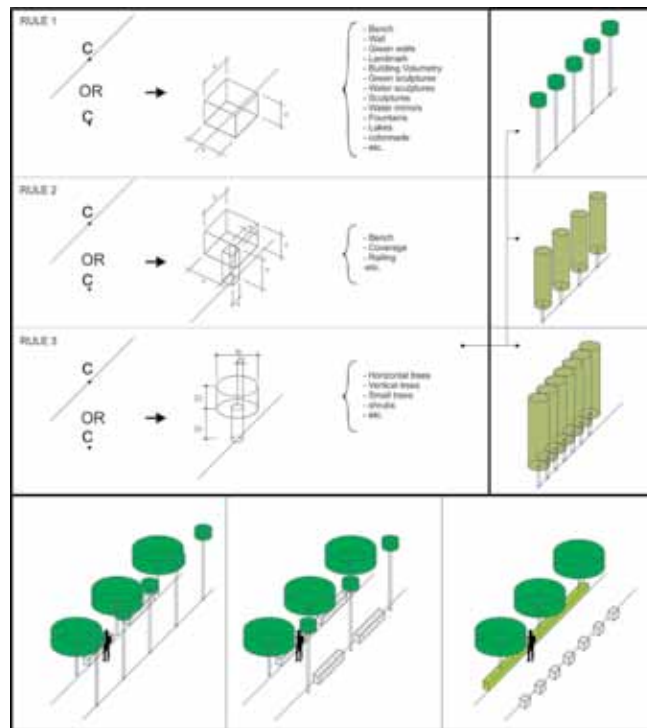


Figure 5. Schematic shape grammar rules.

Figure 5, graph A, illustrates the whole proposed structure implemented in Touchgraph navigator, a software used to organize links and develop mind maps. The class hierarchy can be identified by the circumference around the class name. Super class LD (landscape design) is at the highest level of the hierarchy. As a result, it has the largest circumference, while concepts (pat-

terns) are at the lowest level of the hierarchy with the smallest circumferences. The rules that will show the students how to use a concept are shown on figure 5A. Figure 5B shows an instance of a concept, exemplified by a design solution developed by Roberto Burle Marx.

4. Conclusion

The model presented in this paper is the first step to develop a new pedagogical system that can teach students not just the work of Roberto Burle Marx's designs but of any other designer. It depends on which concepts need to be illustrated. However, it is still necessary to define properties and describe the relation between classes and instances for the system really to be based on an ontology, because an ontology is not only formed by a taxonomy. The next phase in this research will consist of implementing the taxonomy described above in an ontology editor. The goal is to evaluate whether the shape grammar rules and the hierarchical structure developed can really assist students and help them overcome design difficulties.

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CAD SOFTWARE AS CUSTOMISATION TOOLS

Using FBS protocol coding scheme to understand the behaviour of mass customisers

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Abstract. This paper explores the use of CAD software as tools in mass customisation systems and discusses using protocol study methods to analyse the interactions between customers and customisation tools. Current uses of CAD software as customisation tools will be presented. The use of the Function-Behaviour-Structure coding scheme to analyse protocols from customisation sessions is discussed. A protocol from Puma footwear customisation is analysed using the LINKOgrapher software and the results presented. The paper concludes with a discussion on the utility of computational support tools to study designers/customers utilizing CAD tools for mass customisation.

Keywords. Mass customisation; CAD; customisation toolkits; design protocol study; FBS coding.

1. Introduction

Mass customisation is an emerging business strategy that aims to provide customers with customised products with near mass production efficiency (Pine, 1993). In recent years, a number of successful companies have been built around this business model, e.g., Ponoko, Shapeways, Freitag, offering personalised products and services to their customers (Kumar et al, 2007). In addition, leading companies such as Nike and IKEA have adopted mass customisation in parallel with their traditional mass manufactured product lines.

In construction and architecture industries, there have been efforts to adapt prefabricated buildings techniques to allow purchasers to customise a building by selecting and configuring components (Benros et al, 2007).

From a technical perspective, companies have to adopt many advanced technologies such as CAD, rapid manufacturing and online sales to implement a mass customisation system (Helm et al, 2008). From a design point of view, they have to split the design decisions between a product's designer and its end users. Companies make interfaces for customers to customise the product based on their preferences at points of purchase. In many cases these interfaces, known as customisation toolkits (Franke and Piller, 2003), are simplified CAD tools that guide users through typically huge solution space to the customers. Dimensions, functional features, colours and materials are some frequent decisions to be made by customers. For example, IKEA provides a simplified CAD tool (IKEA 2010) to assist its customers with planning their living spaces using a library of IKEA products, Figure 1.

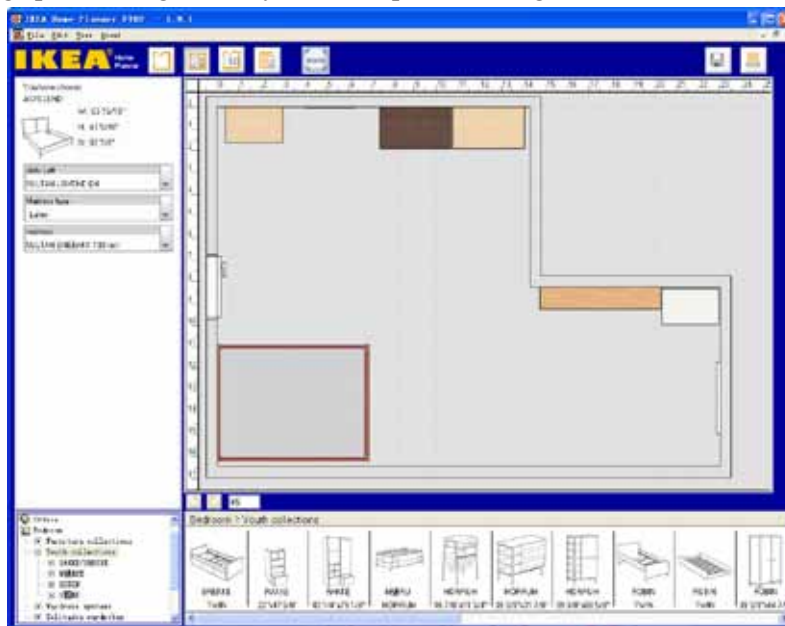


Figure 1 – A screenshot from the IKEA Planner tool

The experience of involvement in the act of design is claimed to be enjoyable for the customers (Franke and Piller, 2004). However, some argue that performing the user-designer role leads to confusion of customers during customisation (Teresko, 1994). This phenomenon, called mass confusion, has

been the focus of several customer-oriented researches in the field (Chen and Wang, 2010; Huffman and Kahn, 1998). Some have argued that CAD tools would not be as useful for customers as they are for designers since most customers don't have the same knowledge and experience as designers do (Piller et al, 2005). As a result, overcoming mass confusion demands more than just providing users with sophisticated CAD toolkits. However, given the design-erly nature of customisation (Pourmohamadi and Saunders, 2009), there is an opportunity to use methods and theories from design cognition studies to examine customers as designers with less, if any, design competency.

In this paper, we discuss adaptation of protocol analysis methods from design studies to analyse the behaviour of customers in mass customisation. The results of a case study are presented and discussed to illustrate the usage and potential of this adaptation.

2. FBS protocol coding scheme

Protocol analysis is a well-established method for acquiring data on thinking from verbal reports (Ericsson and Simon, 1993). It has been used extensively in cognitive and behavioural studies of designers (Bilda et al, 2006; Ennis and Gyeszly, 1991). A typical protocol study consists of these tasks:

- 1. Coding development
- 2. Videoing designers
- 3. Transcription of video
- 4. Segmentation and coding
- 5. Analysis of coded protocol
- 6. Generation of linkograph
- 7. Analysis of linkograph

The FBS coding scheme (Kan and Gero, 2009) is driven by the Function-Behaviour-Structure ontology of design (Gero, 1990). It categorises design activities using six variables (called design issues): Requirements, Function, Behaviour (expected and structural), Structure and Description. The final goal of designing is to transform a set of requirements (R) and functions (F) into a set of descriptions (D). The function (F) of an object is defined as its intended purpose or teleology. The behaviour of the design is either expected (Be) or derived from its structure (Bs). The structure (S) describes the components and their relations in the design. The requirements are variables that are not controlled by the designer but come from a client. There is no direct route from requirements and functions to descriptions and the designer has to go through cycles of transitional processes from one design issue to another.

Figure 2 illustrates the eight transitional processes between design issues:

Formulation which transforms functions into a set of expected behaviours (process 1); Synthesis, where a structure is proposed to fulfil the expected behaviours (process 2); an Analysis of the structure produces derived behaviour (process 3); an Evaluation process acts between the expected behaviour and the behaviour derived from structure (process 4); Documentation, which produces the design or partial design description (process 5). There are three types of reformulation: Reformulation 1 – reformulation of structure (process 6), Reformulation 2 – reformulation of expected behaviour (process 7), and Reformulation 3 – reformulation of function (process 8).

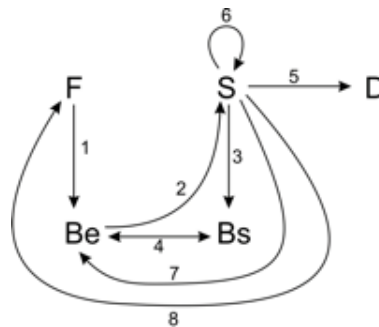


Figure 2: FBS issues and their transition processes (Kan and Gero, 2009)

The FBS based coding scheme converts a verbal design protocol into a series of segments where each segment addresses a single ontological design issue and is labelled by a single FBS code. After segmenting and coding the protocol, a linkograph is constructed by connecting segments based on their semantic relations (figure 3). The sequence of codes in a protocol along with its linkograph is the basis for a variety of analyses (Kan and Gero, 2008). The following section presents a case study of applying the FBS coding scheme to analyse the results of the use of the Puma footwear customisation system.

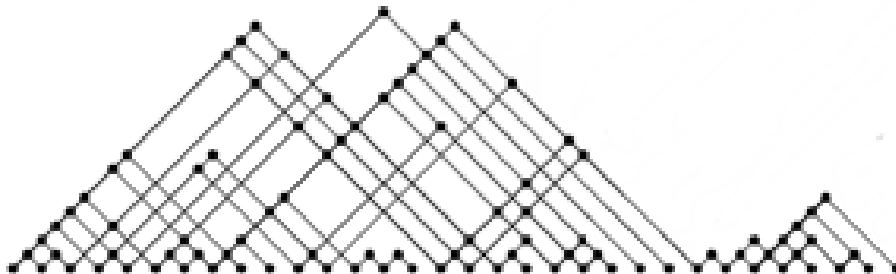


Figure 3: Part of a conceptual linkograph from a coded and linked design session.

3. Case study: Puma footwear customisation

An exemplary case of customisation is presented here to discuss the method and potential of using the FBS coding scheme for analysing users' behaviour during customisation of products.

The task was to customise a pair of Puma shoes using their customisation tool (PUMA, 2010). The participant had no design related background or education. She was asked to verbalise her thoughts and decisions as she customised her shoes. The session lasted for 32 minutes until the participant described the final configuration as satisfactory. Following standard practice for producing data for protocol analysis, the recording of the customisation session was transcribed and coded using the FBS coding scheme twice by the same person with a ten day delay in between each coding session, to check the integrity of the coding. During customisation, the customer plays both client and designer roles. Consequently, one of the questions raised during the coding was how to define which segments are representing Requirement issues that come from client side. To resolve this conflict, we decided to consider any issues that are not the results of a process (e.g. Formulation) as Requirements. For example, if the participant verbalises the leather as preferred material without any prior analysis to decide on leather, the segment has been coded as Requirement. Both codes were then self-arbitrated with an 87% agreement using the Delphi method (Gero and Mc Neill, 1998). The final coded protocol consists of 372 segments including 300 FBS issues and 72 non-FBS segments. In other words, FBS coding was able to cover 81% of the protocol from the customisation session. This is a high degree of applicability, which could be due to similarities between the coded customisation case and general design activities. Table 1 shows an excerpt of the protocol and the code assigned to each segment.

Table 1: An excerpt of the protocol and the code assigned to each segment.

#	Utterance	Code	#	Utterance	Code
34	I don't want suede.	R	43	I want leather.	R
35	Because it's hard to look after	Bs	44	Because it's nice and soft.	Bs
36	Black coffee grain leather.	S	45	And it can expand, too.	Bs
37	I don't want matte.	Be	46	OK. So, if I selected that.	S

3.1. BUILDING THE LINKOGRAPH

Linkographs are built using semantic relations between design segments (Goldschmidt, 1990). From the ontological point of view, each link represents a transition process between two design issues (Gero et al, 2011). For example

a link between a structure (S) and a description (D) segment denotes the documentation process. The construction of the linkograph, like the coding, was done twice, ten days apart, to check the integrity of the relationships identified between segments. To build a linkograph, each segment is linked back to the prior segments that are semantically related to it. This linkograph is called the semantic linkograph to distinguish it from the syntactic linkograph that can be constructed by linking each segment only to its immediately preceding segment.

The linkograph of the protocol is a rich dataset, which allows for a variety of statistical analyses. LINKOgrapher, an open-source analysis tool (LINKOgrapher, 2010), has been used to carry out the analyses in this paper. It performs common analyses measurements related to the FBS coding scheme on any formatted coded/linked protocol.

The linking of the segments is carried out after removing non-FBS segments. There are a total of 755 semantic links in this protocol, i.e., an average of 2.52 links per segment. The following is an introduction of the common analysis methods and the results produced in this study. Since each link has a design issue at both ends it maps onto a design process.

3.2. FBS ISSUES AND PROCESSES DISTRIBUTION

According to the FBS ontology, any design issue falls into one of the six codes and a non-FBS issue is not a design issue. Consequently, the density of design issues and processes in any given protocol is a measure of design activity in that case. One of the possible analyses on a coded protocol is to look at the distribution of the design issues and the design processes in that protocol. This is done by examining the overall distributions or dynamic distributions. In dynamic mode, a fraction of the protocol length is selected as a viewing and calculation window. The window is then moved forward along the length of the protocol one segment at a time and the distributions are calculated for each window position. Putting the results together produces a dynamic view of distribution of design issues and processes during the session.

Table 2 shows the overall distribution of design issues as well as semantic and syntactic design processes in the protocol. In the case of Puma footwear customisation, the overall distribution of segments shows a high frequency of Structure (S) and Behaviour from Structure (Bs) issues in the protocol. This means the participant has tried and analysed many different configuration options during the session. The distribution of design processes also supports the same idea, with Analysis (19.3%) being the second most frequent process after Reformulation 1 (45.0%).

Table 2: The distribution of design issues and processes in semantic and syntactic modes.

Issue	Distribution (%)	Process Distribution	Syntactic (%)	Semantic (%)
Requirement	2.7	Formulation	0.6	0.2
Function	1.3	Synthesis	6.9	6.3
Exp. Behaviour	12.0	Analysis	18.4	19.3
Str. Behaviour	24.3	Evaluation	10.3	9.7
Structure	48.7	Documentation	16.1	12.4
Description	11.0	Reformulation 1	42.5	45.0
		Reformulation 2	4.6	7.1
		Reformulation 3	0.6	0.0

There is a high density of behavioural issues at the beginning (Figure 4), when the participant is listing her needs and preferences. After about 50 segments, the frequency of the structure issues begins to rise, i.e., the participant is trying many different possible options or basically clicking around. But after choosing the material for the quarters the frequency of behaviour issues increases. Dynamic process graphs also show a sharp increase in the frequency of reformulation-1 activities. In other words, the participant tries to match the behaviours of the selected configuration with her initial expected behaviours. Later we will show how information lack is observable at the same time, which is considered as one of the main sources of confusion.

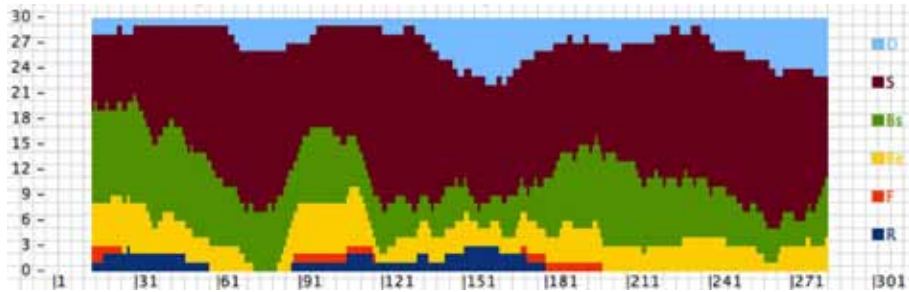


Figure 4: Dynamic Design Issues Distribution in Puma Footwear Customisation Case

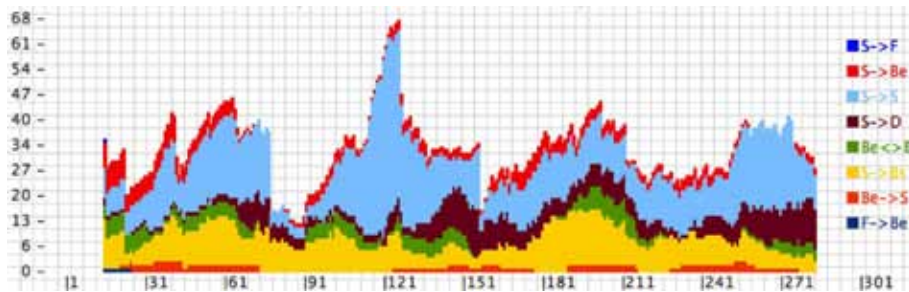


Figure 5: Distribution of Semantic Design Processes in Puma Footwear Customisation Case

3.3. OVERALL AND DYNAMIC ENTROPIES

In information theory, Shannon's (1948) entropy is a measure of the information content of a message. Kan and Gero (2005) suggest entropy as a measure to analyse the potential of design sessions. Similar to design, here a non-linked linkograph means that the customer cannot make relations between the needs (expected behaviours) and the offered solutions (structures) (Piller et al, 2005). A fully linked linkograph happens when the customer knows everything about the offerings so there isn't any new option (Huffman and Kahn, 1998). Though these conditions are not likely to happen in real world cases, they define the ground for our approach toward interpreting entropy of a mass customisation session.

Qualitatively, there are two dramatic drops in the entropy graph of the customisation session shown in Figure 6. The first drop occurs around segments 70 to 90 when the customer is just clicking around and trying different options without any particular reasoning about or analysing those structures. This is close to the condition when there is no link between segments of a linkograph. The second drop occurs between segments 210 to 250. A look at the main events of the session will reveal that the participant is just reviewing the selected configuration, i.e., there are no new ideas being generated.



Figure 6: Dynamic horizonlinks entropy in Puma Footwear Customisation Case

There are a few local rises in the entropy graph as well. The sharpest increase happens around 120 to 150. This is when the participant is generating the main list of expectations for the future shoes and evaluating every configuration against those criteria.

There is a high correlation ($p = 0.01$) between horizonlink entropy and the semantic distribution of design processes, Figures 5-6, i.e., the more the design activity, the greater the information lack the participant experiences. This suggests designerly issues in the customisation session as a potential cause of confusion. However, demonstrating a causal effect between design activity and knowledge insufficiency needs more in-depth analytical studies.

4. Conclusion

As companies shift from mass production to the mass customisation business strategy, they transfer the responsibility for making some design decisions to their customers. To facilitate this transformation, companies provide the users with customisation toolkits. In many cases, the customisation toolkit is a downgraded version of the CAD tool that designers use. Arguably, the customers do not have the design knowledge and experience to use such CAD tools the way designers do. Consequently, they end up being confused in making decisions about the product based on their personal needs and preferences. Appreciating the similarities between design and customisation, we suggested using methodologies from design studies to expand our understanding of the behaviour of customers in customization. In this regard, we chose the FBS coding scheme to analyse the protocols of the customer during customisation. The ontological foundation of this coding scheme allows for its application regardless of ground domain or number of participants.

In this paper we presented a case study of Puma footwear customization using the FBS coding scheme. A non-designer participant was asked to customize a pair of shoes using the Puma configurator. The preliminary results of the analyses are promising as the coding scheme identified more than 80% of the total observed issues in the protocol. The models resulting from the analysis fit our qualitative observations and expectations.

Applying the FBS coding scheme to the study of a single customization case generated promising results in its ability to provide insights into the behaviour of the customer while using CAD software to customise the product. Future studies will include coding and analyzing multiple cases of customization and aggregating the results to obtain statistically significant results.

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RETHINKING CONCEPT DESIGN TOOLS

High-level requirements for concept design tools

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Abstract. In the architecture, engineering, and construction industry there is increasing recognition that design decisions early in the design process create significant project value with relatively small effort. It seems reasonable to investigate what decision support for designers in early phases should look like and what conclusions can be drawn for digital tools that designers employ in those early project phases. This paper introduces and discusses a cohesive set of concept design tool requirements. It explores connections between theoretical approaches in design cognition, experimental implementations, and recent developments in architectural practice responding to very pragmatic problems. The paper communicates results of academic workshops at the Third and Fourth International Conference on Design Computing and Cognition, DCC'08 and DCC'10, respectively, in the context of this ongoing research. At the end, it proposes a systematised model of a desired software tool thus allowing future research to close critical gaps which have hampered progress in concept design tool development.

Keywords: Concept design; requirements; decision support; cognition; software.

1. Introduction

Architectural design activities have been topic of research for considerable time. Since their emergence, digital design tools have been subjects and objects of research, too. Previously, research has focused on specific aspects of digital tools and has produced correspondingly focused results. This paper is part of

an ongoing endeavour to establish a general, yet concise and cohesive, set of requirements for the development of digital concept design tools for the architecture, engineering, construction, and operation (AEC/O) industry within a comprehensive domain framework. The foundation for this research lies in more than two decades of studying and experiencing practices in the AEC/O industry including its supporting software vendors. Since this paper is only the second publication about this research, it is expected to elicit additional discussion, research, and development.

2. Research approach

Because many practitioners and researchers of computer aided design can provide deep insights to this investigation we chose a participatory, discursive approach in the form of a workshop for the crucial part of establishing digital concept design tool requirements. In the following sections we delineate the research domain and establish a set of concept tool requirements based on preceding research. We communicate the results of a workshop about conceptual computational design tools at the Fourth International Conference on Design Computing and Cognition – DCC'10 and proceed with a discussion of the incorporation of these results. At the end, we propose a systematised model of a desired software tool and will conclude with an outline of future research.

3. Research domain

In a previous paper Mueller (2009)¹ assembled research results across the domain of computer-supported architectural design and constructed a framework for concept design tool specifications (Figure 1)².

This framework considers design investigations by all disciplines involved in AEC/O projects throughout the project lifecycle. Adding a third dimension to this domain is the consideration of practice models and related technology. This research aims at pushing higher along the vertical axis, enabling innovative practice models by setting high goals for technology and support digital tools will offer to AEC/O project teams.

Because review of AEC/O industry publications indicates that design decisions early in the design process create high project value with comparatively low amount of effort (CURT 2004) this investigation's goal is to determine what decision support should be provided to designers in these early phases so that pertinent decisions can be made while the relative effort is low. It is noteworthy, that while the focus of the research is on tools for the early design phases, the overarching concern remains the entire project lifecycle (Kohler et al 1997; Ozel and Kohler 2002). In addition, the design investigations that

need to be undertaken during early design expand in cross-disciplinary collaboration as well as in scale spanning from molecular to global, including the traditional building scale.

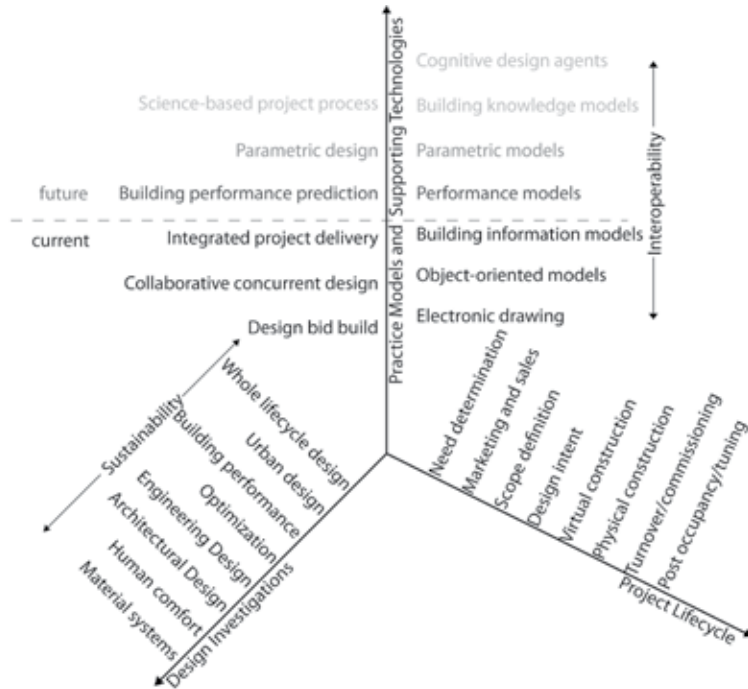


Figure 1. Revised sketch of the research domain space³

Digital tool offerings for the AEC/O industry are numerous. They address many aspects of the domain; however, none appears to be designed based on a set of broad aspects and consistent requirements, but focus on specific features like ease of use or specific types of analyses while neglecting some essential characteristics. Therefore, we discuss in this paper a coherent set of requirements that offers opportunity to identify research and development topics in order to fill any gaps and deliver improved technology for digital design support, moving the bar higher up the Supporting Technologies axis.

4. Concept design tool requirements

In order to be able to address the increasing complexity of the domain and the required veracity in project design, we are asking: what qualities are required in digital concept design tools? A first answer to this question is based on user perspective, followed by presentation of predecessor studies.

4.1. REQUIREMENTS BASED ON USER PERSPECTIVE

From interviews with practitioners and own experience there arise three fundamental requirements for a concept design tool, with a user's perspective:

- *Ease of Use*: an important factor for conceptual design tool selection is how non-disruptive they are to the flow of the design process. Tool operation must not disrupt cognitive processes of designing and interfere with ideation. Designers seem to prefer two groups of tools: very simple tools that are limited but highly intuitive, like pencil and paper; and tools that they know well. Interpreting affordance and intuition as expressions of familiarity or experience, one conclusion is that with increasing literacy in digital tools more aspects of them will appear intuitive.
- *Modelling Capabilities*: given ease of use, designers gravitate towards tools they know support generation of the design artefacts that express their formal design intent.
- *Visualization Capabilities*: given ease of use and modelling capabilities, designers prefer tools that let them show their designs in the light and visual expression that align best with the state of their design and highlight the experiential notion they want associated with their designs. A design that cannot be communicated effectively to others is a risk designers seek to avoid.

4.2. REQUIREMENTS BY BERENTE ET AL

In the cognitive sciences the discussion about support of design activities through information technology is over a decade old (Boland 1994 as referenced by Berente et al 2008). Berente et al identify the following principles that need to be resolved by systems capable to support distributed heterogeneous design teams. These principles are relevant to this research, because "Such networks are becoming more prevalent as innovative design activity is increasingly distributed across diverse contexts" (Berente et al 2008):

- *Semantic Coherence* allows design collaborators to use different representations by supporting semantic reconciliation of views.
- *Synchronization* establishes periodically a state of the design by consolidating all changes that have occurred up to that point in time.
- *Representational Flexibility* refers to the need of supporting the variety of representations used by designers, their generation, communication, and purposes.
- *Regenerativity* describes the capability to recreate geometry in order to effectively understand aspects of the design.
- *Temporal Traceability* means the capability to step through a design's history interactively to understand how the design developed.
- *Spatial Traceability* refers to designers' need to be able to correlate representations and explore them transverse to their representational planes to understand

the spatial nature of the emergent design.

4.3. REQUIREMENTS FROM DCC'08 WORKSHOP

In a workshop at the Third International Conference on Design Computing and Cognition – DCC'08, we, together with the other participants, discussed the concept of affordances as approach to defining conceptual design tool requirements. The discussion generated the following list with references to Berente et al:

- *Multiplicity* means support of many designers and many data-flows with various workflows for each designer. It affords method and tool selection based on the design problem. It supports multiplicity of opinions in a community for knowledge exchange.
- *Flexibility* as expansion of Representational Flexibility describes support of changing interface modes, for example 2D, 3D, sketching, and haptic devices; flexibility in choice of representational modes, including mathematical representation of geometry; flexibility in workflows; extensibility as additional tool flexibility.
- *Simultaneity* allows for concurrent models with Semantic Coherence; pursuit of simultaneous, parallel paths of design; side-by-side investigations, for example of parameter set history, relationships, and solution spaces. It includes Synchronization and aspects of Temporal and Spatial Traceability.
- *Representation of the Environment*, like climate, topography, and context.
- *Semantics* as expression of semantic information with Semantic Coherence.
- *Entity Identity* as consistent, non-redundant objects with multiple, unambiguously linked representations.
- *Emergence* as possibility to change the semantics of a representation in order to let it play a different role in the design.
- *Entity Linkages* for dependency relationships between entities or elements including aspects of Temporal and Spatial Traceability.
- Representation of *Abstract Objects* and Phenomena, like ideas, culture, experience, notions, associations, and other non-building information.
- Support of *Diagramming* and Diagrams.

Overlaps between sets of requirements can be at least partially explained by the longevity of the discourse. Some themes have been in discussion for almost one and a half decades. As confirmation of their relevance it is to be expected that themes recur in subsequent examinations of the issue.

5. Unified set of concept tool criteria

5.1. FIRST CRITERIA SET

In order to unify the criteria in support of a consistent discourse, for this research the following set of requirements was considered meaningful:

- Ease of use.
- Modelling capabilities.
- Visualization capabilities.
- Multiplicity.
- Flexibility in interfaces and representations including diagram support.
- Simultaneity including synchronization, temporal and spatial traceability.
- Environment providing full environmental context for design activities.
- Semantics expressing semantic information with semantic coherence.
- Entity linkages including enabling of temporal and spatial traceability.
- Abstract objects.
- Diagram support.
- Regenerativity as capability to reconstruct model data for understanding.
- *History* from Temporal Traceability, perpendicular to simultaneity.
- *Design Space Exploration* as consequence of the domain space, as the capability to browse and learn from previous designs or design alternatives.

5.2. CRITERIA SET RATING

In continuation of this discursive investigation, we conducted a workshop at DCC'10. We provided this set of criteria with descriptions to workshop participants. They conducted a survey to establish a tentative ranking of the proposed concept design tool requirements. Participants were asked to rate importance of requirements with 1 for most and 5 for least important. Grading was based on an inverse point system with 5 for most important and 1 for least important (Table 1). According to the survey, requirements in order of importance are: *Semantics*, *Flexibility*, *Modelling Capabilities*, *Visualization Capabilities*, *History* and *Design Space Exploration*, *Environment*, and *Abstract Objects*.

In the discussion changes of labels and confluences of some of the requirements were suggested, as well as perceived shortcomings pointed out:

- Visualization Capabilities to Externalization or Representation to emphasize reduction of focus on visual senses.
- In terms of geometric form, visualization capabilities and modelling capabilities are tightly linked.
- Modelling Capabilities should include “automation from abstract rules”.

- Diagram Support and Abstract Objects have common aspects.
- Environment and Abstract Objects have common aspects.
- Attributes like Semantics should be able to be “switched ON and OFF”.
- Regenerativity was misunderstood as “generative modelling”.
- Participants missed support of ambiguity.

Table 1: Concept design tool requirements survey from DCC’10 workshop.

Ease of Use					1			5.00
Modelling Capabilities	2		5		4	1		9.75
Visualization Capabilities		1		3			5	7.67
Multiplicity	5						3	2.67
Flexibility		4	2		2	2	4	10.00
Simultaneity								0.00
Environment	3	5		4		3		5.58
Semantics		2	1	1	5	5		14.50
Entity Identity								0.00
Entity Emergence								0.00
Entity Linkages								0.00
Abstract Objects			3			4	2	5.42
Diagram Support		3						1.67
(Re)generativity							1	5.00
History and Design Space Exploration	4		4	2	3			6.67

It should be mentioned that the rating of the Requirements represents, other than their importance, also their absence in present software tools. Characteristics that are already available, like geometry representation, for example, are not mentioned, neither high rated even if they are obviously very important.

6. Discussion

These requirements are quite heterogeneous in character and do not stand at the same level of generality. For example, Modelling Capabilities include Entity Linkages and Abstract Objects, while Flexibility may refer to all three: Modelling Capabilities, Representation Capabilities and Semantics. Some of the requirements represent desired modes of work within the design medium, e.g. Diagram Support, while others refer to interactions within and between these modes, like Flexibility and Simultaneity, or to interactions with sources

external to any one particular software, as does Design Space Exploration. Ambiguity arises from Flexibility of Semantics and Representation Capabilities. Finally Ease of Use is ubiquitous to all of them and depends a lot on the way of interaction with the digital design object; it is a function of the Interaction Medium. This is why the characteristics of a desired concept design tool were schematized, as seen in Figure 2. All mentioned requirements can be found at different places on this diagram, sometimes covering whole axes or regions.

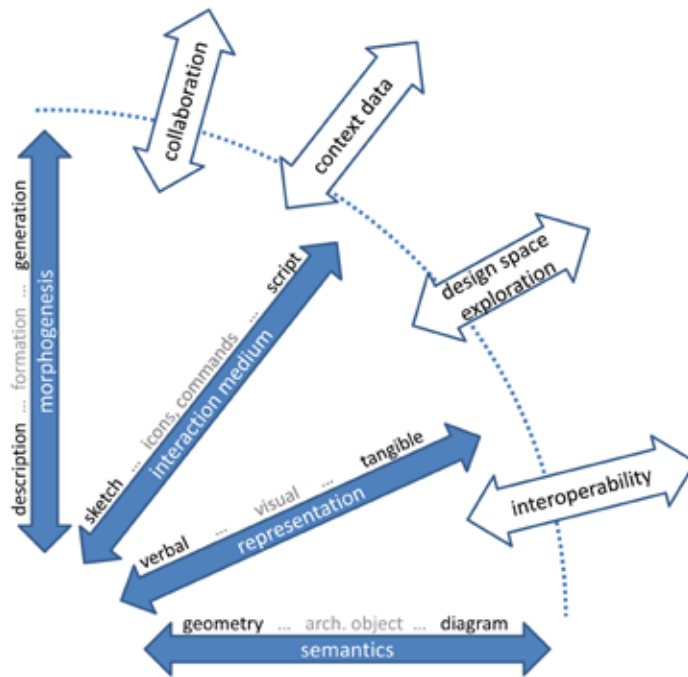


Figure 2: Aspects of software for architectural design.

In this proposed model, four major aspects for a concept design tool are identified: *Semantics*, *Morphogenesis (Form Creation)*, *Interaction Medium*, *Representation*. The idea is that there is a continuum of states on each of these axes and a good concept-design tool should offer them all in order to support creativity and architecture well. Examples of combinations from different states on each axis are:

- Directly creating geometry by sketching while the system automatically creates rules from the sketch.
- Generating geometry by scripting.

- Creating architectural objects with semantics through sketching.
- Describing architectural objects with semantics through building information modelling.

These examples represent various modes of work or workflow. A designer should be able to switch back and forth from one state to the other on each axis, ensuring Multiplicity, Flexibility, Entity Identity and Entity Emergence. History can be assured as a function of time. The other, outer, arrows represent characteristics which are linked to the software but are not contained in it and show relations to other software, data or actors in the design process. Studying this scheme, the requirements can easily find their place and the gaps in the present software tools become evident.

7. Conclusions

The sets of requirements described in this paper demonstrate the challenge a high-level approach to digital tool design poses. At each iteration, the criteria set were changing due to lack of agreement about terminology, inconsistent categorical levels in the sources and in discussions, or disagreement in importance of the criteria. Considering the large domain space that a successful AEC/O concept design tool needs to be able to cover, even when focusing only on the initial project stages, this result comes as no surprise.

That is why we propose a systematic schematization of a concept design tool, comprising four major aspects and additional features linking a particular tool to other actors, data, software or context. Even though this is a first publication of this scheme and it would necessarily undergo some alterations suggested by the CAAD community, the idea is that a given piece of software could be mapped to this scheme and examined against its aspects and features, in order to determine what is lacking and develop it according to the rated priorities of requirements.

Continuation of this research will attempt to pursue the following investigations: theoretical testing of the validity of the concept design tool model, determination of the next level of detail to these high level goals, and construction of a wide spread of use cases that occupy various locations in the model.

Endnotes

1. Please refer to this paper (Mueller 2009) for more detail about the domain space and an extensive review of relevant, substantiating references.
2. Figure 1 has been modified for this paper. A horizontal dashed line representing the estimate of the current state of practice has been introduced on the vertical axis. The Discipline Axis has been renamed Design Investigation and additional markers identify

activities mentioned in the 2009 paper but not shown in the preceding version of this figure.

3. Detailed explanations of the items on the axes are in Mueller 2009.

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THE POLYMORPHIC DIAGRAM

On mediating spatial thinking in architecture design

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Abstract. This paper describes the polymorphic diagram, a conceptual building information modeling environment conceived to mediate spatial thinking during the conceptual design phase. In particular, the discussion is focused on how enabling multiple forms of representations can possibly support and improve architects' cognitive capacity to reason about space configuration.

Keywords. Space configuration; conceptual design; diagrams.

1. Introduction

The conceptual design workflow has been described as the most cognitively intensive phase of the whole design process (Kim et al 2008). Architects mediate the complexity of the conceptual design phase through iteratively modeling the design situation, structuring the relationships between the various entities of the design situation (Cross 2007). Drawing on literature concerning design studies and cognition, the traditional diagram has been the most dominant means of modeling or "structuring" the design situation. Diagrams have been recognized as the architect's dominant medium of thought and knowledge creation (Herbert 1993). Thinking with diagrams enhances the architect's mental ability to manipulate design knowledge and information (Do and Gross 2001), enabling the architect to bridge the gap between the design problem and the conception of a fitting and responsive solution (Alexander 1964).

Nevertheless, it may be observed that, despite of diagrams' invaluable role in thinking during the conceptual design phase, emerging shifts in contemporary design production are imposing significant limitations on the cognitive

and developmental traits of the traditional conceptual diagram. In contemporary design workflows, a holistic examination of knowledge and information is rapidly becoming a critical criterion for effective architectural production. That is to say, designers require a conceptual design medium that enables them to seamlessly interact with larger sets of information that can be reliably and readily integrated, transformed, repurposed, and communicated. Diagrams are becoming increasingly limited in these regards.

These limitations in representing and manipulating the complex matrix of design knowledge and information have prompted urgent demands to investigate new design mediums to support architects during the conceptual design phase. A prominent approach has focuses on developing design systems that augment the cognitive traits of diagrams with layers of computation and information technology.

In its contribution to this space of research and development, this paper describes the polymorphic diagram, developed and conceived to support an important cognitive capacity for conceptual design thinking: spatial reasoning through multiple representations of design knowledge and information (Lawson 1997; Akin 1998). In essence, the polymorphic diagram is a conceptual building information model that supports structuring the design situation by allowing design information to be represented and repurposed in various forms of abstractions and different levels of complexity.

2. The polymorphic diagram

Following the same fundamental principle as BIM technology, the polymorphic diagram enables the structuring of design knowledge in a central and integral repository. Then it allows the designer to engage this knowledge in multiple forms of representations that are best suited to the design task at hand. Nevertheless, the polymorphic diagram is especially targeted at the conceptual design workflow with an emphasis on spatial reasoning and configuration. Accordingly, it is based on an entirely different implementation when it comes to interfacing with the underlying information model. Broadly speaking, this difference manifests in both interaction and representation. Unlike existing BIM systems, where designers typically interact with discrete representations of building components (such as walls, columns, slabs, etc), the polymorphic diagram gives focus to spatial considerations represented through a simplified abstract notation. This abstract notation is inspired by bubble and blocking diagrams. Such diagrams are important cognitive and developmental mediums with wide applications in conceptual design thinking and spatial reasoning.

3. Objectives and method

The conception and development of the polymorphic diagram fits within a larger research project. The primary objective revolves around investigating how digital design media can support spatial thinking during the conceptual design phase. The discussion below presents an empirical study undertaken to help shed light on how digital design media can support spatial thinking. In particular, it looks at how offering multiple forms of conceptual representations can possibly enhance architects' ability to configure space and its topological relationships. The experiment is abstract in nature. In other words, it is not meant to carry out the design of a particular space or building typology. Instead, it was intended to work with an important yet abstract concept of space: space adjacency.

The experiment itself involves configuring a set of blocks to fit given boundary conditions. The configuration of these blocks is to follow a set of generative spatial patterns while avoiding a set of degenerative ones. The notion of spatial order was developed to measure the success and positive arrangement of the blocks' configuration. A stronger accommodation and accordance with these patterns yields a higher spatial order. On the other hand, evidence of degenerative patterns lessens the overall spatial order. It should be emphasized that what is of interest here is how designers examine and negotiate these spatial patterns. More specifically, the study hopes to investigate how moving between different representations modalities can improve the designers' capability in configuring these blocks in light of these spatial patterns. To investigate this capacity, four advanced architecture students were asked to participate in this study.

The experiment was carried out in two phases. Participants are presented with boundary conditions along with a set of blocks that may differ in both size and color. The participants are then asked to configure the blocks to fit the given boundary conditions with the objective of maximizing the spatial order. In the first phase, participants proceed with the space configuration exercise using only one representation modality: the blocking representation. The participants attempt to configure the blocks to achieve the highest possible spatial order. To bring to light the potential value of multiple forms of representations in spatial thinking, the configuration exercise is carried out again. Phase two, however, involves selecting two participants (referred to as Group B). This group is to be supported with a second representation mode: the graph representation.

It was hypothesized that using multiple forms of representations will improve participants' capacity to reason about space, achieving improved spatial order in this experiment. That is to say, with the use of a second rep-

representational mode, participants belonging to Group B achieve a spatial order for their configuration that exceeds both Group B's initial attempts and that of Group A's second attempt.

Before discussing the results of this experiment, it is important to further elaborate on the concept of spatial patterns as they relate to this study. In particular, what is meant by spatial patterns, and how do they influence – either positively or negatively – the spatial order of the configured blocks?

3.1. SPATIAL PATTERNS

The notion of a spatial pattern here refers to an abstract construct used to represent and manipulate established concepts of space such as space adjacency, distribution, clustering, stacking, etc. In this early experiment, emphasis is placed on space adjacency. Representing this spatial concept was achieved through defining structures of relationships in terms of block properties. There are three block properties that form the basis of defining spatial patterns: size, color, and linkage. Both generative and degenerative patterns are derived from some logical combination of these properties.

Block properties and their variations are used to enable a wide variety of spatial elements. These properties include size, color, and linkage. There are four block sizes: 1, 4, 9, and 16. The unit value for a given block is, basically, the square root of its actual size. Color is used to distinguish between classes of space, three in total – two serviced spaces colored green and orange and one service space denoted with a gray color. Links represent a graphical notation used to determine the linkage between two adjacent blocks – whether linkage exists and, if it does, in what direction?

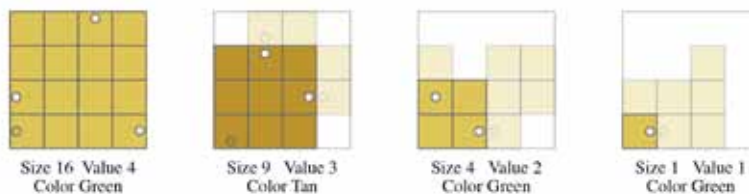


Figure 1: Block properties: Size, color, and linkage.

Spatial patterns could be realized in one of two modes: generatively or degeneratively. A designer's ability to achieve a positive configuration of the blocks is contingent on articulating relationships between the different space enti-

ties in accordance with a list of generative specifications while avoiding degenerative ones. Again, the specifications underlying the generative and degenerative patterns are abstract. They are not designed to particularly suit or address actual space planning situations. Nevertheless, they are established to help study and shed some light on how designers negotiate spatial properties and how working with different forms of representations can assist the architects in carrying out this important design workflow.

Before going over the spatial patterns, however, consider these conditions and general rules governing block linkage.

- Each block has a number of links equal to its unit value. These links can be interactively moved around within the block itself based on the designer's discretion.
- All links in a given block must be used. If a link is not used, it must be nullified. Users can nullify a total of 3 links per configuration.
- Links are used to establish linkage between two adjacent blocks. Two blocks are considered linked if they are adjacent and their links are aligned with one another.
- Each link has a direction of flow. The direction of the link flows always from the smaller block to the larger block.
- Void links indicate that blocks of similar color cannot use this particular link. Rather, to make use of that link, a block of a different color must be used.

3.2. SPATIAL PATTERNS

Space adjacency is a spatial pattern manifests in the quality or state of being adjacent, or of lying near contiguity. In any built environment, spaces are typically grouped in a manner that supports and achieves a more successful and appropriate operation. In the context of this experiment, this spatial concept has been simulated through defining desired situations for associating blocks together to achieve a positive (generative) application of this spatial pattern. Below is a list of generative situations. The degenerative situation for this spatial pattern is anything that negates or violates the situations listed below.

- AD1: Each block with a size greater than 1 has adjacent blocks whose collective value is equal to its size. However, exceeding the value is permitted if the block lies adjacent to the boundary line.
- AD2: Each block should be adjacent to a number of service blocks equal to its unit value. The remainder of the adjacent blocks (as determined by AD1) must be of the served space class.
- AD3: Green blocks have an additional adjacency criterion. In particular, these spatial elements must have more cells lying on the boundary of the configuration than otherwise.

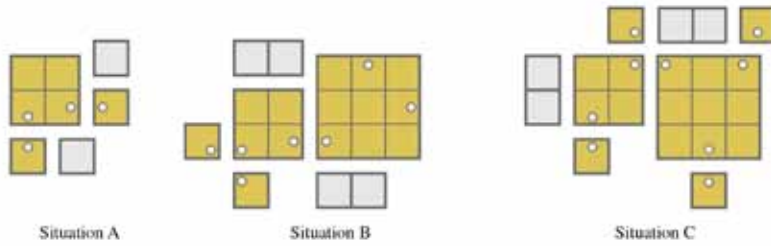


Figure 2: Block adjacency. Situation (A) presents a generative adjacency pattern, while situation (B) and (C) present degenerative patterns. Specifically, situation (B) violates AD1, and situation (C) violates AD2.

3.2. SPATIAL PATTERNS

The notion of spatial order has been briefly presented above. It is a metric developed in this experiment to measure the success of a participant's spatial arrangement. It can be determined as follows: Consider the different spatial patterns covered in the exercise (only adjacency, in this study). For each specification (see Section 3.1), evaluate its appropriate application. For each block in the configuration, placing it in accordance with the pattern's specifications would earn units equal to the block's value. On the other hand, each violation would deduct units equal to the block's value. In addition to the pattern specifications, there are certain arrangements that would earn additional points. They can be used to further enhance the spatial order. These patterns include edge complete, edge sharing, edge surround, edge interlock, and edge inward.



Figure 3: Different situations to enhance spatial order for a given adjacency configuration. Different colors here are not indications of class difference. Instead, color is used to distinguish the blocks from one another.

Edge complete is achieved by situating support blocks on a single edge, as shown in Figure 3.a. Edge sharing is achieved by situating two blocks of

similar size but different classes such that they share an edge, as shown in Figure 3.b. Edge surround is achieved by surrounding a block with blocks of smaller size. Edge interlock involves two blocks of similar size but different classes. These blocks are offset by one cell where a block of size 1 is added to simulate the interlock. Edge inward is achieved by situating a block next to the boundary while pushing its links inward.

3.4 DIGITAL DESIGN ENVIRONMENT

The experiment is carried out using our prototype for a digital diagramming medium, one that supports the capacity to reason about space using multiple representation modalities. It was intended for the diagramming environment to provide a simple, almost austere environment to help designers focus on configuration tasks. In connection, special attention was directed toward inter-actively manipulating the blocks. Selecting, moving, and linking blocks were central issues throughout our development.

Besides its role in facilitating spatial thinking, the diagramming medium was developed to track designers' moves and evaluate the spatial order manifest in their work. This analytical feedback technique was used to interpret and discuss participants' results for this experiment.

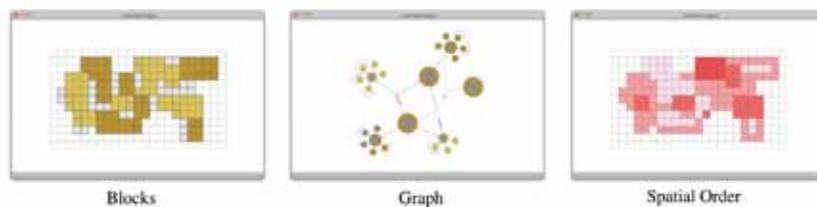


Figure 4: The experimental diagramming medium with multiple representation modalities.

4. Experiment results

Each student participant produced two configurations. The spatial order for these configurations was determined based on the generative and degenerative specifications for the space adjacency pattern (see Section 3.1). Figure 5 depicts the spatial order for each spatial configuration. For each row in the figure, a participant's first and second attempts are shown. Further to the right is an interpretation of the rate of spatial order improvement. The overall improvement rate measures how many more cells are in a generative state. On the other hand, the pattern-improvement rate measures how many more cells have been configured in desired generative pattern state, as explained

and depicted in Figure 3.

5. Discussion

From the results depicted in Figure 5, a basic observation can be made. In all of the space-configuration attempts, there was improvement in spatial order. That is, the spatial order in phase 2 is higher than that recorded in phase 1.



Figure 5: Spatial order results for each of the experiment participants.

In interpreting and analyzing the results, we looked at the rates of improvement recorded for the spatial configurations for both groups. It was found that the rate of improvement in the spatial order when using a second representational mode was significant, moving from 3% to 24%. This improvement

relates to the configuration results. But what about the configuration process itself? What is the effect of using a second representational mode?

In examining the feedback attained from the design environment, it can be said that the participants in Group A used a smaller number of moves to reach their block configuration. In a thirty-minute time period, Group A used 833 and 1002 moves, whereas Group B used 1197 and 1381, respectively. Working with multiple forms of representations will increase the number of moves used to negotiate and manipulate the spatial order.

Further examination of the moves reported by the experimental diagramming environment makes it clear that the designers in Group B used 483 and 601 moves in working with the graph environment, an average of about 39% of the total moves. These moves were used to establish relationships, as indicated and specified in Section 3.2. Participants then worked on working out these spatial patterns and relationships in space. On the other hand, Group A did not have the ability to build these relationships and use them as the basis for their spatial negotiations. Participants in Group A expressed that they had to use memory to work with these patterns and negotiate their situation. This is, perhaps, reflected in the significant increase in the number of blocking representation moves that they used.

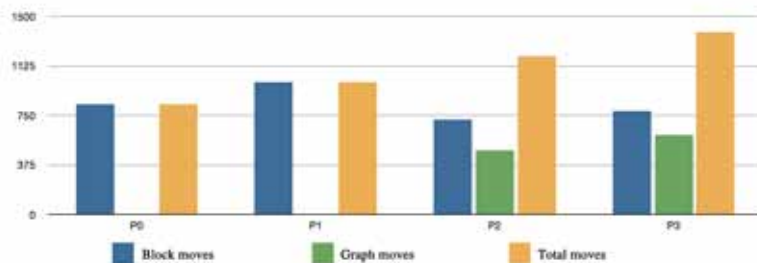


Figure 6: Number of space configuration moves used by Group A (P0,P1) and Group B (P2,P3).

In light of the results attained from this experiment, the hypothesis of this paper was validated. That is to say, using a second representation modality indeed led to improved spatial order, a more successful and responsive space configuration.

6. Conclusion

Reasoning about space and its configuration lies at the center of the conceptual architectural design workflow. It is the architect's mean of modeling

the design situation, bridging the gap between its problem definition and its emerging proposition. Paradoxically, however, modeling spatial information (knowledge about the design problem's spatial requirements and its topological configuration) is the least well-developed feature in modern design systems. Moving forward, modern design systems must pay heed to this fundamental design faculty. It must extend its ability to assist architects in representing, manipulating, and evaluating spatial patterns and configurations. One of the key approaches in realizing this development revolves around bridging the gap between traditional and digital media. Specifically, this approach investigates the prospects for augmenting the cognitive traits of diagrams with layers of computation and information technology.

This paper presented and discussed the polymorphic diagram, a conceptual building information modeling environment. The scope of the paper focused especially on the role of representation in supporting spatial thinking during the conceptual design phase. The experiment presented in this paper has shown that designers' capacity to reason about space configuration is improved when working with multiple forms of representation.

The importance of such findings has long been recognized in the literature on design studies. Nevertheless, the role of such findings and contributions in shaping modern design systems can hardly be traced. Admittedly, the experiment presented above involved a small number of participants. Hence, its results can hardly be generalized. Nevertheless, its value lies in hinting an important direction for future design technology development and contributes to its methods of implementation. It is hoped that such contributions from developing the polymorphic diagram, would help shape design technology to complement and extend BIM's important offerings to include modeling the design situation, especially its spatial requirements and its topological configuration.

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ASSESSMENT OF DESIGN TOOLS FOR IDEATION

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Abstract. Designers interact with a wide range of design tools, in a variety of ways, in order to support their work. Any attempt to produce digital tools aimed at supporting ideation raises the question of the kind of information considered account and what is appropriate to the needs and expectations of designers. We developed and implemented an assessment method for digitally supported conceptual design based on *reflective conversation, flow, cognitive ergonomics* and *activity theory*. Our approach opens up the evaluation spectrum to include parameters beyond performances factors for conceiving new digital design tools. This assessment approach considers user (the designer), action (ideation) and object (the tool) in the ideation process, namely the designer's experience interrelated to the needs of the task and the characteristics of the tool. In this paper we present the results of several research protocols in which we observed, analyzed and successively acted upon five different stages of the interface of a design tool as it was being developed, the Hybrid Ideation Space (HIS). Taken as a whole, these results suggest the limits and support of designers' optimal relationship with an ideation interface.

Keywords. Ideation; assessment method; design tools; human computer interaction.

1. Introduction

We frequently speak well of the sophistication of computer-based tools and the revolution they have brought to the activity of design in how we act and interact, but we seem to forget that the initial design process, the conceptual design phase, is still done with freehand sketches. At this point, most digital tools do not support ideation in the way they should, partly because most of them were conceived for other purposes and other disciplines. We need

to look into the development process of digital tools that support conceptual design in order to understand why these tools play a limited role compared to sophisticated representations of already conceived ideas. This paper presents the results of several research protocols in which we observed, analyzed and successively acted upon five different stages of the interface of a design tool, the Hybrid Ideation Space (HIS) (Dorta, 2007), as it was being developed. The HIS supports sketching and working with physical models in an immersive environment dedicated to ideation. The assessment method in this study for digitally supported conceptual design is based on reflective conversation (Schön, 1983), flow (Csikszentmihalyi, 1990), cognitive ergonomics (Hutchins, 1995) and activity theory (AT) (Kuuti, 1996). Teams of two industrial design students worked in the HIS during the conceptual phase of an ad-hoc design project. The ideation process inside the HIS was examined through video analysis as well as questionnaires. Three levels of activity were considered for the video analysis: operation, action and activity level support. The results from each successive protocol have led to pertinent improvements to support designers' cognitive processes, making the HIS more intuitive with every modification.

2. The challenge of evaluating digital tools

Over the last three decades, design research has largely focused on computer-centered tools imitating hand-driven design. Many studies (Gross et al, 1996; Stappers, 2003) which compare computer-aided design (CAD) systems with sketching to identify how well these support conceptual design, show two results: CAD systems are at a disadvantage to support ideation, considering how sketching suits designers' cognitive process. The CAD/sketch comparisons do not reveal the kind of support designers need during ideation. Digital tools often have an interface conceived with the principles of human computer interaction (HCI), that sees the interface's usability as critical. But HCI research addresses the evaluation of design tools in a different way: 'Conceptual design receives scant attention in HCI literature, with the balance of research firmly on technical developments and system-specific evaluations' (Sener, 2005). Salim and Burry (2010) discussed the key requirements for CAD systems and proposed the notion of *software openness*. Where the 3D parametric software is openly customized, allowing the exchange of information often needed by architects and engineers, as well as a better integration of physical and virtual information, making the transitions between these environments seamless. New ways of interaction with CAD systems are in constant development, such as the Wiimote plug-in for Autodesk Design Review

by Autodesk Labs (Sheppard, 2009). The Wiimote is used for navigation through the 3D models. This combination of sensor and physical computing devices has the potential for innovative ways of designing. Consequently, as pointed out by Salim and Burry (2010) software openness in parametric design tools will depend on the compatibility of the physical and omnipresent computing. The demand for supporting creative design thinking and multi-disciplinary design with digital tools is influenced by how design tools are developed (propose) and the assessment (how the tools respond to designer's needs). Software openness explored the potential of CAD systems in design but there is a trend to think outside the digital screen that is changing the interfaces of design tools. Any attempt to produce digital tools aimed at supporting ideation raises the question of the kind of information to be taken into account and what is appropriate to the needs and expectations of designers. In order to find how digital tools can support better ideation, it will be necessary to go beyond improvements or changes of existing design tools and develop different assessment instruments.

3. Conceptual design and digital tools

During conceptual design, concepts supporting the designer's cognitive process are ambiguous, imprecise and abstract (Bilda, 2003). Naturally design tools have to match this process, preserving these characteristics of conceptual design. Representations such as sketches are abstract and open for interpretation. Designers can generate ideas in different ways such as verbal or visual (Oxman, 2002). It is the designers' speech and gestures that give meaning to their representations thus moving forward the design. In order to bring in digital tools during the conceptual design process, they need to support not only freehand sketching as a data input but also all the elements involved in conceptual design (gestures, annotations, verbalization). As Hernandez (2006) has pointed out even parametric design, once considered highly specialized, is today usual in the traditional CAD systems. This incorporation of parametric models responds to designer's demands for more freedom of manipulation and transformations of 3D models during the design exploration process. However, parametric variations multiply when parametric design becomes increasingly complex in the chaining of changes resulting in an inflexible model (Blurry and Blurry, 2008). Oxman and Sass (2006) presented the Digital Design Fabrication (DDF) method as another option to produce concepts in the early stages of design modeling combining generative computing and rapid prototyping. However digital tools typically channel all input through the mouse, therefore all these software tools feel the same to the designer's hand (Djajadiningrat et al, 2004). Designers still explore their

concepts using physical modelling as well as a way to communicate complex design ideas in architecture (Cuff, 1992). Several research approaches have emerged with the promise of developing computerized tools for conceptual design such as the Envisionment and Discovery Collaboratory (EDC) (Arias et al, 2002). This system attempts to maximize the richness of face-to-face communication between different actors involved in the design process mediated by both physical and computational objects. The Share Design Space (Haller et al, 2006) is another system that allows collaboration in a face-to-face setting with sketches using an AR-based tabletop environment. All of these systems support different modes of design drawing. They were developed to replace the keyboard and mouse and allow designers to use the computer like a pencil on paper. This approach seems to be logical, given that sketches are the best way to support conceptual design.

4. New assessment method

The assessment method proposed in this study is based in the principle to examine all that should be considered when conceiving interfaces for digital conceptual design tools. First we borrow from Schön's the notion of 'Reflective conversation', based on his observations of professionals' behavior and performance. Secondly, the concept of 'Flow' defined by Csikszentmihalyi, which is based on a state of concentration when there is no consciousness of effort. We triangulate this information with 'cognitive ergonomics'; in particular through cognitive aspects, (mental representation, memory), perceptual aspects (attention, recognition, perception) and psychological aspects of the human task. The combination of flow and reflective conversation tell us to what extent the designer perceives his performance to have increased or decreased. The relationship of cognitive ergonomics to reflective conversation address the 'cognitive load' involved in the ideation activity. Pairing cognitive ergonomics with flow allows the observation of the 'interaction' between designers and design tools. In a previous study we used the concept of flow to develop what we call Design Flow (Dorta et al, 2008). The Design Flow allowed us to observe the engagement of the designer as it unfolds during ideation. Furthermore, we measured the workload of the task as part of the Design Flow. The actions during the activity (ideation) depend on the goals and the context in which is realized. The video analysis considers three categories based on the activity theory that examines the relation between the subject and object in which the tool is the mediator. The following section summarizes the mains aspects of each category:

- **Operation level support addresses the basic actions of the activity.** Eye

and hand coordination: when the participant was able to sketch looking at the representation; manipulation of the interface: clicking on the menu options; outcome: agreeing on one idea; pointing with laser pointer and talking: explaining or share an idea; pointing with laser pointer: moving the laser pointer like sketching.

- **Action level support allows the observation of the designer's actions to accomplish the activity.** Sketching and talking: thinking aloud or sharing an idea while sketching; sketching looking at the representation: sketching while focusing the attention on the representation; sketching looking at the screen: sketching while focusing the attention on the screen; involved with the representation: sharing or explain an idea with the help of the representation; sketch verification: looking at sketch and reflect on it; sketching and looking at the screen of the iPod; looking at the screen: when the participant's attention is draw to the screen (this apply only to the participant that is not sketching).
- **Activity level support focuses on the main goal, which is the ideation.** Ideation /Co-design: when the participants work and use the interface at the same time; cooperation: when the participants divide the task even if they use the interface at the same time.

There is another section for technical problems, preparing the settings, training and interface issues. The last one addresses the moments when the participants were not able to find a command or when the information in the interface was not clear.

5. Setting of the experiment

The protocols were done in a system that combines immersive sketches with and physical models: the HIS (Dorta, 2007). One particular aspect of this system is the immersive environment where designers sketch and make models all around them in real-time and life-size scale using a digital tablet (sketches) and image capture (physical models). The system allows effortless design conversations between virtual and physical models, which are important in architecture. It has also been used for interior and industrial design. Teams of two industrial design students (second year) worked in the HIS during the conceptual phase of a design project. The ideation process inside the HIS was examined through video analysis as well as questionnaires. A selection of videos from each year was analyzed, particularly the first 10 minutes. The first moments of interaction with the interface are very important since this is when the participants get used to it. From 2007 to 2009 work sessions of 35 teams per year were recorded. The time for each session was 20 minutes per team. From 2007 and 2008 the HIS had a digital tablet (Cintiq® 21") as an input device. The participants were sketching with the help of a spherical template, but this required an adaptation from them since the template caused

a deformation on the sketches. One participant was sketching while the other was using the hands to point at the representation. In order to give them more freedom they had a laser pointer. In 2007 three teams used only the Cintiq® then the Cintiq® and the laser pointer. Three more teams used the Cintiq® and laser pointer in 2008. In 2009 the spherical template was changed for a corrected drawing area where the participants sketch without deformation. In addition, another input device was tested: the pen tablet (Wacom™). This time, five teams used both input devices and the laser pointer. Also in 2009 four teams tested different interfaces of the HIS: PC tablet (Modbook® 13"), Wacom™, iPod and two laser pointers. The drawing area was improved in the Modbook® following automatically the orientation of the user's sight by using a rotating device. In all the protocols the participants used the HIS for developing the concept of a car as an ad-hoc project. Figure 1 summarizes the different settings for each year.

Setting of the experiment							
YEAR	2007		2008		2009		2009
Input device	Cintiq®	Digital Tablet Cintiq® 21" screen	Cintiq® laser pointer	Digital Tablet Cintiq® 21" screen	Wacom™ laser pointer	Pen Tablet Wacom™	Modbook® laser pointer
	Cintiq® laser pointer	Digital Tablet Cintiq® 21" screen			Cintiq® laser pointer	Digital Tablet Cintiq® 21" screen	Modbook® iPod
							Wacom™ laser pointer Laser pointer laser pointer
TEAMS	3		3		5		4

Figure 1. The settings of the experiments from 2007 to 2009.

6. Results

Figure 2 shows the results of the participants using the different combinations of input devices from 2007 to 2009. In 2007 (1) the participants spend between 4 and 6 minutes sketching and looking at the s Cintiq's screen. Sketching on the spherical template required the students' attention on the screen as well as some time for adaptation. However, the students that didn't have the laser pointer were more involved with the representation (1). With the incorporation of the laser pointer the students improved their design conversation by pointing and talking about their sketches (2). In 2008 (3) the participants were still sketching and looking at the Cintiq's screen (5 min). Nevertheless they were more involved with the representation and the use of the laser pointer increased significantly (4 min). The participants spend more time sharing concepts and agreeing on their ideas (co-design). By 2009 (4 and 5) the drawing area was implemented in order to avoid the deformation. Even with the use of the drawing area the time for sketching and looking at the Cintiq's screen was

6 minutes (5). This is almost the same time as with the spherical template in 2007. The participant's attention was focused on the Cintiq® due to size of the screen. The Wacom™ doesn't have any screen and the students needed to look at the representation all the time (4). Because of this they were more aware of the immersive environment as well as their partner's actions. However the students spend more time trying to draw straight lines and less time defining their concepts. In all cases the students were able to develop a concept as well as maintain a design conversation.

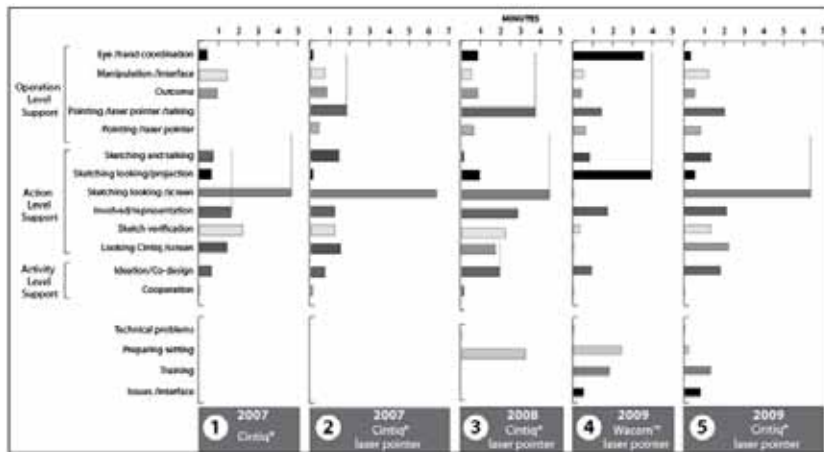


Figure 2. Video analysis of different input devices in the HIS (2007 to 2009).

6.1. FOUR INTERFACES

The data from the previous protocols showed that the interface could have an impact in the way the participants work. In order to improve the ideation process four different interfaces were tested in 2009 (Figure 3). The Cintiq® was replaced for a PC tablet (Modbook®) keeping a smaller screen as a direct feedback of where to sketch. This time the participants were able to sketch with the laser pointer. Sketching directly on the representation with two lasers pointers allowed the participants to moved freely and sketch at the same time on different parts of the representation. But they only shared their ideas after their sketches were finish working in cooperation (4). The hand eye coordination was not a problem but moving the whole arm for sketching was not natural for them (Figure 3). The combination of the Wacom™ and the laser pointer (only for pointing) (3) allowed the students to sketch looking at the representation as much as with the two lasers (4 minutes). However they spent more time trying to sketch what they wanted and less time discussing their

ideas. With the Modbook® and iPod (2) the participants sketched simultaneously and each student started to sketch on their own just like with the two laser pointers.

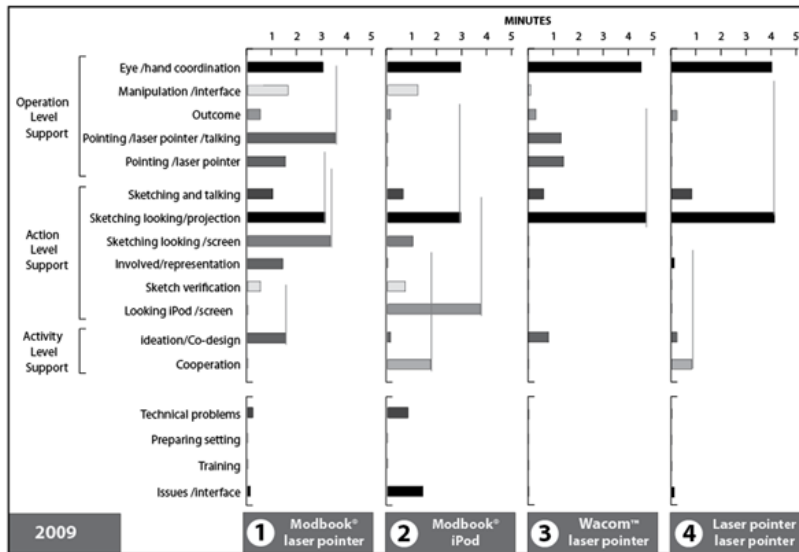


Figure 3. Video analysis of four interfaces in the HIS (2009).

The students worked in cooperation for 2 minutes (2). The participants with the iPod were looking almost all the time at the iPod's screen (4 minutes). The student with the Modbook® was able to sketch looking at the representation (3 minutes). The combination of the Modbook® and laser pointer (only for pointing) (1) was the most efficient. The students spent the same amount of time (3 minutes) sketching and looking at the representation as well as using the laser pointer and talking. They discussed more their ideas and agree on them (co-design, 2 minutes).

The flow and workload questionnaires (Figure 4) were applied only to the Modbook® and laser pointer and Modbook® and iPod. The reason for this is because the laser pointer as an input device was still in a prototype phase and the Wacom™ was tested before. With the results from the video analysis, flow questionnaire and workload is possible to see their relationship in order to do a general assessment of the ideation. The interface that obtained the best results was the Modbook® and laser pointer because the students were more involved, focused and willing to redo the experience, thus performing better (Figure 4, flow Q). The results from the workload confirm this with lower effort, frustration and higher performance (Figure 4). The video analysis showed that the students expressed, shared and reflected more on their

ideas. They were engaged in design conversations that required higher mental demand (Figure 4, workload). But, their performance was also higher and required less effort showing that they worked better with the interface. The interaction with the Modbook® was always intuitive for the participants since they were sketching in a manner similar to paper and pencil.

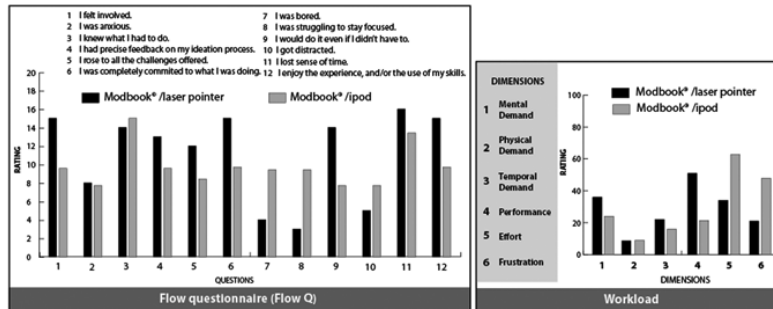


Figure 4. Flow questionnaire and workload (2009).

7. Conclusions

The video analysis confirmed some of our observations in previous studies and provided new guidelines for what could be the next interface in the HIS. Having a smaller screen in the rotating device encouraged the participants to take advantage of the representation while they sketch. But with two sketching devices the participants tend to work in cooperation. The concepts discussed here (reflective conversation, flow, cognitive ergonomics and activity theory) provide a framework for understanding ideation and for fostering design tools. The presented assessment method do not necessary convey the completed evaluation of the ideation process. However, by combining all four concepts, it is possible to expand the field of study and link results (crossover) to produce an approach that will build a unified body of knowledge. In order to provide a convenient new assessment method, further testing will be needed. At this stage the overall goal of the assessment is to verify if this framework still reflects the experience adequately and if the knowledge extracted can inform the next design iteration for the conceptual tool.

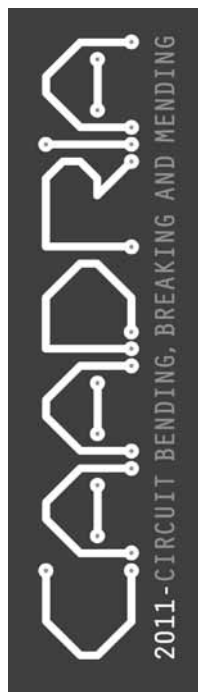
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COMPUTATIONAL DESIGN ANALYSIS



COMPUTATIONAL DESIGN ANALYSIS I

42.	Complex adaptive residential quarter planning using multi-objective optimization: An agent-based modeling approach <i>Seongki Lee and Ludger Hovestadt</i>	433
43.	Applying interpretation-driven association to design domains <i>Kazjon S. Grace, Robert Saunders and John S. Gero</i>	443
44.	Exploiting instability: Reconfiguring digital systems <i>Linda Matthews and Gavin Perin</i>	453
45.	Computational method for mapping quality of architectural space <i>Aswin Indraprastha and Michihiko Shinozaki</i>	463
46.	The territory of the personal workspace: Development of the PWAS (personal workspace analysis system) <i>Mariko Enoki, Yoichi Hanada, Yuji Matsumoto, Nagisa Kidosaki, Ryusuke Naka and Shigeyuki Yamaguchi</i>	473
47.	Data flow and processing in the computational fractal analysis method <i>Michael J. Ostwald, Josephine Vaughan and Stephan K. Chalup</i>	483

COMPLEX ADAPTIVE RESIDENTIAL QUARTER PLANNING USING MULTI-OBJECTIVE OPTIMIZATION

An agent-based modeling approach

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Abstract. This paper presents a complex adaptive residential quarter planning software. It is developed using Java object oriented programming language and targeting at configuring the tower-type apartment in a dense area during early design stage. Rules are analyzed and formulated based on building code and zone ordinance. Moreover we develop an agent-based modeling with multi-objective optimization algorithm. In this modeling, each agent acts independently according to the rules that are designed to solve the complex geometric problems that are related to physical constraints. At the end, we present a simulation outcome of a case study.

Keywords. MOOP; Urban design; residential quarter planning; agent system

1. Introduction

1.1 DESIGN PROCESS

Residential quarter planning in itself is a multi-objective problem similar to many other real-world problems. Design decision-making process involves varied tradeoffs among multiple objectives, which should be optimized simultaneously. Depending on the information size of the target problem, the amount of both incoming information and outgoing information that is processed with by a designer is enormous. During early design stage that is specially admitted to be one of the most important steps, it is requested to acquire many tangible

design solution candidates (Zeisel, 1984; Simon, 1996; Lawson, 1997).

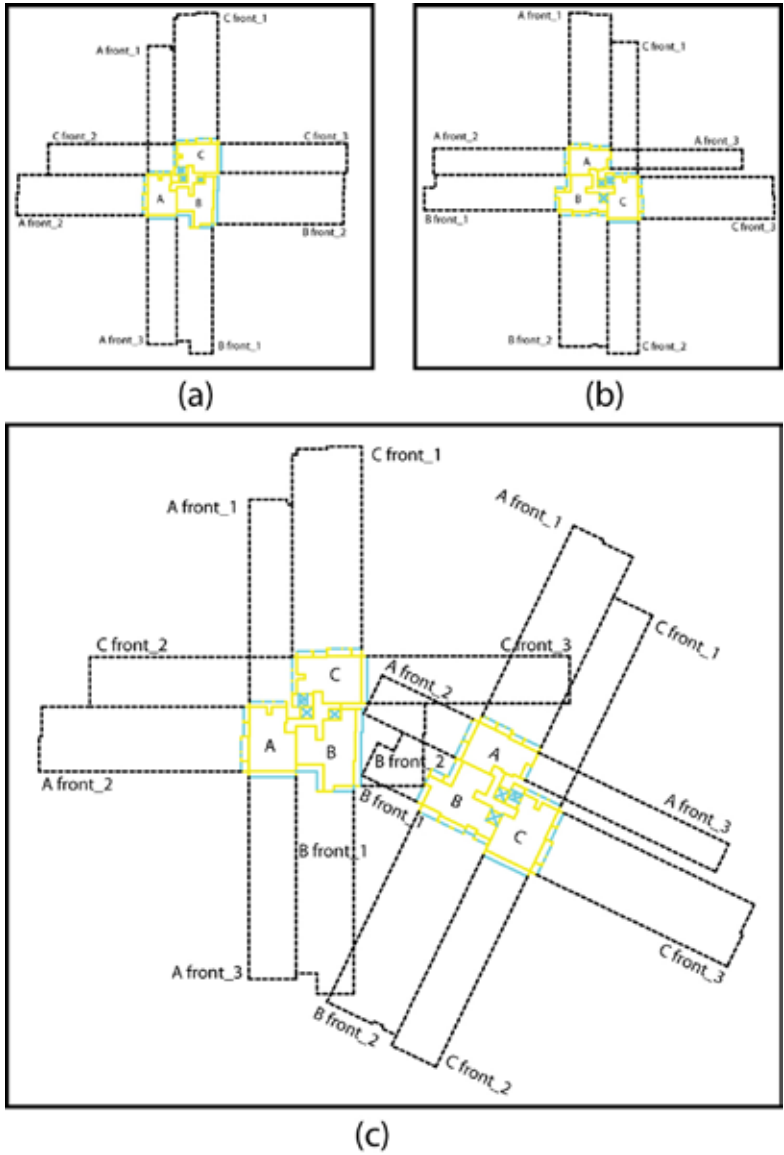


Figure 1. Tower-type apartment cases and distance constraints (a) Tower A, (b) Tower B, and (c) frontline casting from units

The reasons for that are to minimize the risk to select wrong idea and to obtain more feasibly creative design. However it is not easy to acquire satisfactory design spaces within given duration when human's cognitive ability becomes the major resource to navigate many intermediate design alternatives. Solution evaluation that is designer-led with very little computational support can be largely subjective as well. Multiple design objectives to satisfy and various constraints to comply with are insufficient and are violated respectively in some circumstances. Those reasons lead to the limitation of conceptual design decisions. In this research, we develop a residential quarter planning software based on multi-objective optimization procedure.

1.2 RESIDENTIAL QUARTER PLANNING IN SOUTH KOREA

In residential quarter planning with high-rise apartments in South Korea, the distance between facades of units of respective apartments is the key constraint to decide the maximum height of an apartment. When the average maximum storey is calculated with 'the building-to-land ratio' and 'floor area ratio', a designer arranges the preferable tower-type apartments to figure out the possible building configuration. At this time, distance between apartments is generally considered as objective index to consider the openness (view), daylight, and privacy. Figure 1(a) and 1(b) are typical tower-type apartments in Korea, which are arbitrarily named as Tower A (587m²) and Tower B (660m²) respectively. Tower A is composed of vertical stacks of three units: Unit A (186m²), Unit B (186m²), and Unit C (213m²). Tower B is another type composed of vertical stacks of three units: Unit A (150m²), Unit B (186 m²), and Unit C (188 m²). In case of Tower B, three units (Unit A, Unit B, and Unit C) commonly share the core at the lower level. But there are instances where only two units are at the higher level without one unit. If a façade of a unit in an apartment has opening over 50cm wide, the frontline of the façade with a predefined maximum length is extended horizontally to the façade of neighbouring apartments. When the extended frontline from one apartment meets the facade of other neighbouring apartments, the distance in-between is calculated. This process is repeated until all distances are calculated. Finally the shortest distance among distance values of a unit can guide the maximum height of the stack. If we assume that two apartment are arranged as shown in Figure 1 (c), 'B front 2' of unit B of Tower A is shorter than 'B front_1' of unit B of Tower A in relation to the neighbouring Tower B. Therefore 'B front 2' decides the maximum height of the stack of unit B of Tower A. The maximum height of the respective units of the apartment can be calculated in this way and the maximum height of the apartment is acquired from the maximum height of the respective units.

2. Agent based modelling

In this research, agent-based modelling (hereafter ABM) is utilized not to provide a description of a specific system but to solve the residential quarter planning by adapting the ABM theory. ABM is composed of autonomous decision-making entities called agents (Bonabeau, 2002; Macal and North, 2007). Each agent acts independently according to the rules and execute its pre-programmed behaviours. Repetitive competitive pro-actions and reactions between agents are important features of the proposed ABM similar to other general ABMs.

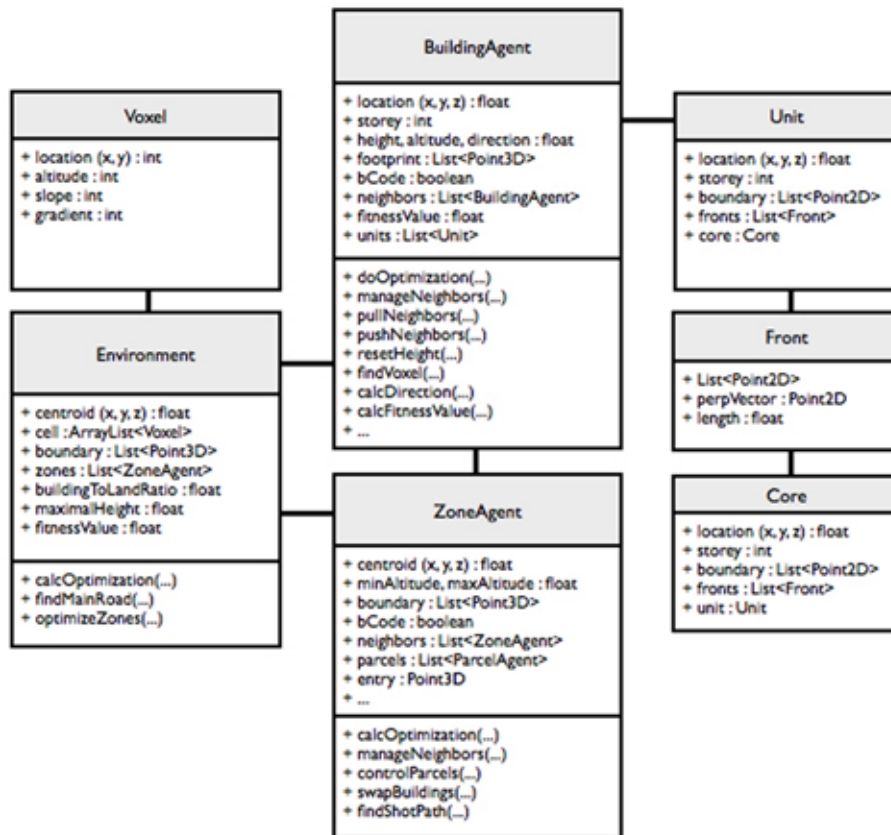


Figure 2. Agent-based modeling for residential quarter

In this proposed system, two kinds of agent are modelled; one is building agent and the other are zone agent as shown in Figure 2. Environment of the ABM is modelled based on GIS information of the target site. However instead of

precisely designing learning system that is found of importance in general ABM, specially designed rules are utilized to help each agent find a suitable behaviour and to assist a program operator to obtain meaningful planning. Emergent phenomena that are captured at the local area between neighbouring building agents can explain the clear relationship between agents. Global phenomenon can be thought as design proposals that we wish to obtain at the end. Whether the outcomes are feasible or not can be decided by optimization technique as following next.

3. Optimization

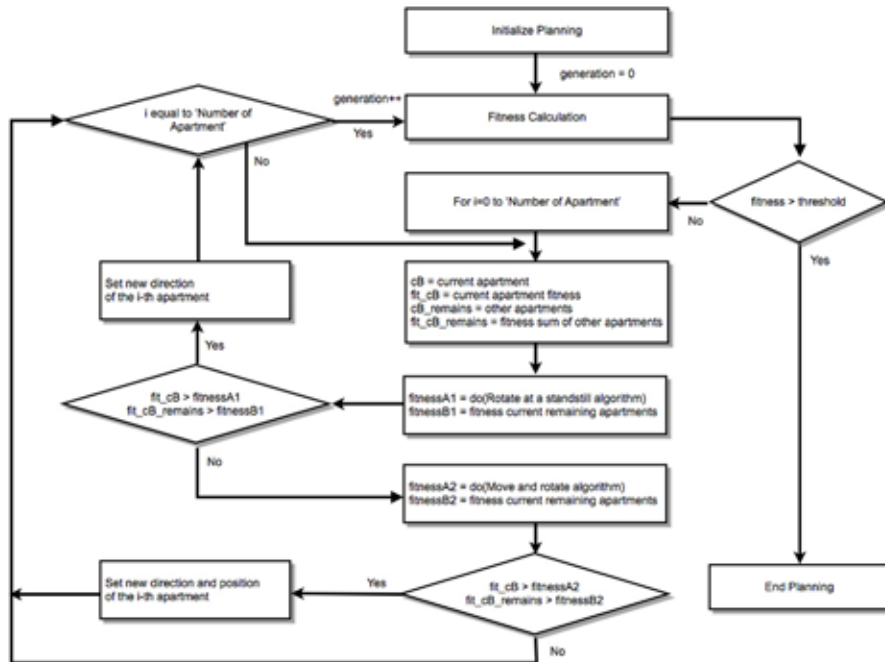


Figure 3. Apartment optimization algorithm

The word of “optimization” refers to the process of searching for the best of all possible candidates to the problem of interest based on certain performance criteria (Papalambros and Wilde, 1991). A general formulation of optimization finds the best solution by finding either the maximum or the minimum value of objective function by varying design variables under the given design constraints (Haftka and Gürdal, 1992). Deb (2002) states the general formula-

tion of multi-objective optimization problem (MOOP) as follows:

Minimise	$f_m(x)$,	$m = 1, 2, \dots, M$;	Objective functions
Subject to	$g_j(x) \geq 0$,	$j = 1, 2, \dots, J$;	Inequality constraints
	$h_k(x) = 0$,	$k = 1, 2, \dots, K$;	Equality constraints
	$x_i(L) \leq x_i \leq x_i(U)$	$i = 1, 2, \dots, n$.	Variable bounds

Where $x = x_1, x_2, \dots, x_n$ is design variables; M is number of objective functions; J and K are number of equality and inequality constraints, respectively; n is number of design variables; and, $x_i^{(L)}$ and $x_i^{(U)}$ are lower and upper bounds on a design variable, x_i . In this study, four objective functions considered to be important for the residential quarter planning; view (f_1), economy (f_2), density (f_3), and direction (f_4). View means relative visual area that can be seen from an apartment. View is calculated by considering both sum of areas that are extended from each front line and possible maximal area. If a 'Tower A' is the ten-storeyed apartment and there are three units sharing a core at from 1st floor to 6th floor, two units at 7th floor and 8th floor, and one unit at 9th floor and 10th floor respectively, the core that is shared by units is not operated economically. Economy is calculated by considering the number of units sharing the core at each floor and the maximum storey of the apartment. In order to reflect the 'the building-to-land ratio', it is important for an apartment to reach maximum 'total floor area'. Density is calculated by a ratio of the acquired 'total floor area' to reach maximum 'total floor area'. And the direction function reflects the building's direction and the land aspect. One unified fitness function of an apartment can be calculated by introducing weighted sum fitness function (Coello, 2001) as follows:

$$F_i = w_1 \times f_1 + w_2 \times f_2 + w_3 \times f_3 + w_4 \times f_4, \quad i = 1, 2, 3, \dots, n$$

$$F_{\text{generation at } g} = (F_{(1, g)} + F_{(2, g)} + \dots + F_{(n, g)}) / n$$

Where F_i means a weighted sum fitness of an apartment and $F_{\text{generation at } g}$ means a weighted sum fitness of a residential quarter at generation g . n means the number of apartments in a residential quarter.

4. Algorithms

This section presents the three algorithms of the computer program: (1) apartment allocation, (2) apartment optimization, and (3) branch road generation. The main structure of the programs is shown in Figure 4.

4.1 APARTMENT ALLOCATION

Apartment allocation technique is used for an initial spatial design. An apartment model is positioned on level x with initial random location. Direction and height of the apartment are computed with the given site information. When a number of apartments are positioned at the beginning in order, already-positioned ones are used as references for the will-be-positioned. Subsequently, the next apartment is positioned, such that the input constraints are satisfied. This process is continued until all apartments are positioned while 'the building-to-land ratio' is not violated. When the initial setting ends, multi-objective optimization is processed until all apartments reach a user given fitness considering threshold.

4.2 APARTMENT OPTIMIZATION

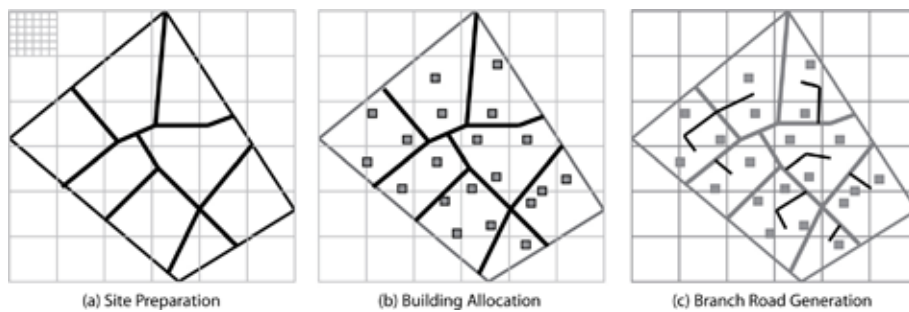


Figure 4. Algorithm steps

The algorithm to improve both each apartment and the residential quarter is created. At the beginning, fitness of each building is calculated without changing geometric information. Then 'Rotate at a standstill algorithm' or 'Move and rotate algorithm' is performed procedurally as shown in Figure 3. For example, 'Rotate at a standstill algorithm' only change the direction of the current optimizing apartment. To change the direction, both fitness value of the current apartment and fitness value of the remaining apartments except current apartment are less than that of the proposed apartment and that of the remaining apartments except the proposed apartment.

4.3 BRANCH ROAD GENERATION

When the optimization process is terminated, planning branch roads can be generated. With the centre points of the apartments and residential quarter boundary, Voronoi diagram (Berg et al, 2008) can be obtained and each cell

boundary segment is reconstructed as an acyclic graph for path finding algorithm. The acquired convex polygons are reshaped to rectilinear shapes by intersection condition. Generally three points meet at an intersection point and one of the smallest angles can be modified to the right angle. Which results in a relatively straight line and it can contribute to the economic planning of the branch road system. The process of building road systems among zones is dependent on both the distance from each zone to access points of the residential quarter and the gradient angles of graph edges constructed from zone boundaries. A connecting path from a zone to one nearest access points can be efficiently computed by Breadth-First Search (BFS) algorithm (Goodrich and Tamassia, 2010). If necessary, closed loop road can be made by linking two neighbouring graph vertices. The end product of this algorithm is a series of road segments applied with breadth. Occasionally by linking buildings of a zone to one of road vertex nearby, a cul-de-sac road can be generated. Too much road area certainly occupies free space; branch road algorithm is designed to minimize the road area within a zone. Additionally there is freedom for a designer to add road segment in order to make through road, loop road, and ring type road. When this algorithm is complete, all building secure accessibility to one or more entries.

5. Implementation

Planning residential quarter can be shaped to three steps: Preparatory stage, intermediate stage, and determining stage.

Preparatory stage has site analysis, site data, and design knowledge acquisition, which is a prior process before running the software. Site analysis is the work of exploring the site to decide which items need to be admitted. Site data is composed of several elements such as topographic information and transportation. A site can be imagined represented by voxels uniformly spread on the site. Agents use the information of a voxel (a vector or a cell in a grid system) by comparing two locations. A voxel is used as a reference in order to assist agents to decide their behaviours as well. Aspect, slope, and altitude are chosen as important elements when it comes to housing complex planning and design in a hilly site. Data of those is precisely gathered by processing digitized elevation model (DEM) with ArcGIS package.

- Aspect is classified to ten discrete directions including north, northeast, east... northwest, and none.
- Slope is calculated by degree ranging from zero to 56°.
- A voxel on the site has an aspect value, a slope value, and an altitude value.

Additionally very important factors such as building to land ratio, density,

and zoning are gathered, which are used as parameters later on. Intermediate stage is a process about manipulating the tool. A main task is to calibrate parameters, which is necessary because if the predefined parameter values are not appropriate, it is impossible to get good solution candidates. Therefore it is indispensable to adjust the initial parameters. Determining stage is the process of solution space selection. Rather than sorting solution space in a descending manner, this stage tries to get feasible solution set, solutions of which will be reflected one by one by human evaluators. So the only one solution that is evaluated as best both quantitatively and qualitatively will be selected as most possible candidate that will proceed to the next design stage. The town design tool is programmed using Java programming language. As mentioned above, the system admits basic information of the site. Basic information is encoded as CSV, XML, and BMP file type based on the information characteristics and process function. To achieve an effective calculation, a set of rules that is used to evaluate the temporary design alternatives is heuristically calibrated. Using a set of rule, it generates design alternatives together with analysis data. 3D geometry data encoded with XML is especially preferable for the interoperability with BIM.

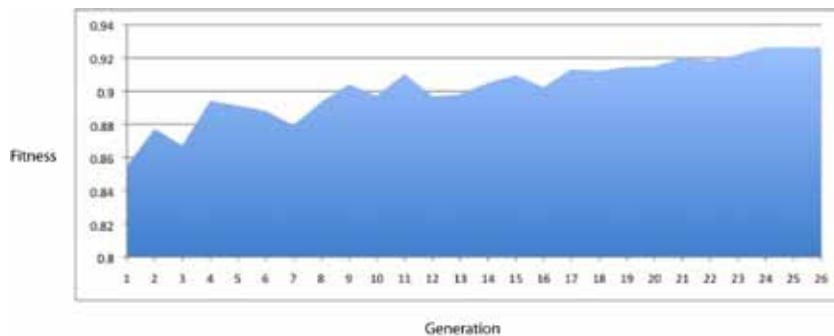


Figure 5. A record of fitness value of the target site at each generation

The target site is located in the centre of Seoul and the new town project is ongoing right now for the purpose of revitalization of the old town by highly dense apartment complex. Figure 5 represent fitness values at each generation. At the initializing stage, the software finds suitable location for each new apartment that the fitness value is relatively high. Which increases the possibility to reach the optimal fitness value that is greater than threshold. This process ends when fitness value (0.926556502) is over threshold value (0.925). Figure 6 shows the interface of the residential quarter planning software. Because of complex geometric calculation, only one area was simulated and all buildings have relatively good fitness value.

6. Conclusion

Rules are analysed and formulated based on the currently shared planning constraints in Korea. This paper associates multi-objective optimization principle to agent based modelling to deal with residential quarter planning in Korea. Even though the tool is designed for residential quarter planning specially targeting at high dense area in Korea, its application to other similar contexts is possible. We assume that this tool can generate feasible residential planning solutions during the conceptual design stage in practices if rigorous methods to deal with more constraints can be found.

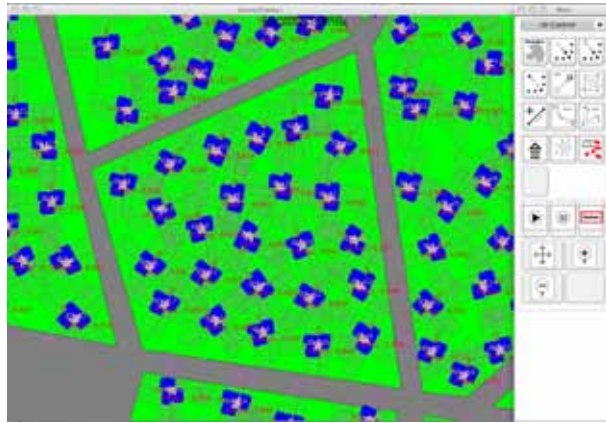


Figure 6. Software interface

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APPLYING INTERPRETATION-DRIVEN ASSOCIATION TO DESIGN DOMAINS

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Abstract. This paper presents a computational model of visual association-making. Our model focuses on the interaction between the processes of representation and matching in association. Re-interpretation of the objects being associated changes the landscape in which the matching process is searching for potential mappings between those objects. We call this process interpretation-driven search. We demonstrate the capabilities of our system through some examples of previous work in simple shape domains, then discuss ongoing research into applying this system to design domains.

Keywords. Visual association; interpretation; computational model; design cognition.

1. Introduction

The process of association is the construction of a mapping between shared aspects of two objects. This fundamental cognitive process underlies analogical reasoning and related processes such as metaphor, allegory and case-based reasoning. Each of these processes is of interest to design researchers, with analogy in particular being recognised as an important component of creative design (Goel, 1997). Modelling association independent of these processes allows us to focus on the way object representations are constructed, which has been identified by a number of analogy researchers as an important area of focus for computational models (French, 2002; Kokinov, 1998). This paper presents a computational model for developing associations founded on a cognitive approach. The paper demonstrates an implementation of this model and discusses the utility of such a system in understanding and assisting designing.

We understand association as being composed of three processes: *representation* of the objects, *matching* between the objects and building a *mapping* around that match. If these processes are modelled serially a chicken-or-egg problem arises. How does the representation that encodes a particular mapping arise before the mapping itself? Representation must occur in parallel with matching and mapping, so that the way objects are conceptualised evolves in conjunction with how they are mapped. We have developed a model of association, exemplified in the visual domain, that focuses on the iterative interaction between the search for mappings and the construction of representations, an interaction that we call interpretation-driven search.

This exemplary model focuses on visual associations, i.e. associations between the structure of visual elements within objects rather than the causal and functional relationships between those elements. Visual analogy has been identified as an important domain in design, creativity and problem solving (Davies and Goel, 2001). The system presented here forms associations between collections of line shapes like those that might be found in sketches, plans or visual design elements. Our intent for this ongoing research project is to apply our system to real-world design domains.

Computational models of association and analogy have potential applications in both understanding how human designers use those processes and in design support systems research. Realising this potential represents a significant challenge in developing systems with the robustness and portability necessary to produce meaningful results in a variety of design domains.

2. A computational model for interpretation-driven association

The model described in this paper can be decomposed into three interacting processes, seen in Figure 1. *Perception* is the system that describes objects it encounters, *mapping* is the system that relates those objects; and *interpretation* is the system that changes the descriptions of the objects.

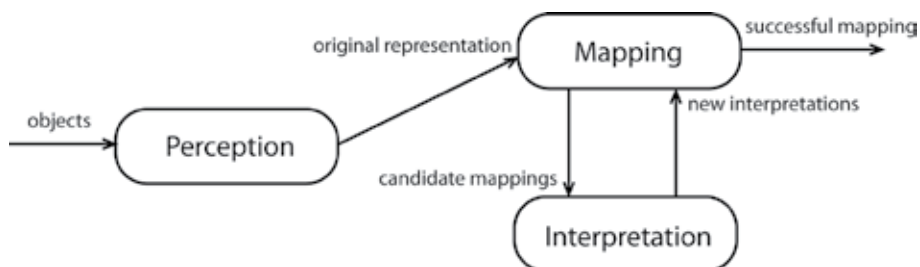


Figure 1. The structure of the interpretation-driven association system.

Low-level representations of the two objects are provided to the perception process, which discovers features within those objects and categorises them into concepts, creating new conceptual categories where necessary. In the implementation described here, features are line shapes and the low-level representations provided are vector images. The perception process also extracts topological and typological relationships that exist within each object from the features and concepts it has created. Each object is represented by a graph of its features and the relationships between those features. The mapping process then searches the two graphs for identical patterns of relationships between features. Whilst this search is occurring the Interpretation process can change the structure or content of the graphs. Interpretation and mapping iterate until a suitable mapping is found.

2.1 PERCEPTION.

The perception process forms the representations of objects that our system uses. These representations form a baseline from which interpretations are applied during its search for mappings. In the implementation described in this paper representations are composed of shapes and of relationships between those shapes. Shapes are individual visual features detected, described and categorised by the system, and the relationships between them are both typological and topological. This element-and-relationship representational structure is consistent both with work in analogy-making (Gentner, 1983) and design thinking (Gero, 1990).

The perceptual processes used in the system are influenced by previous objects the system has seen. Shapes are categorised based on similarities in their descriptions, and these categories, which we call “concepts” are generated and populated at run-time. A shape that is unlike any previously encountered will generate a new conceptual category, and future shapes judged sufficiently similar will be added to that category. This concept formation is accomplished using an unsupervised clustering algorithm operating on the descriptions of shapes. The purpose in including these constructive behaviours is twofold; firstly the less the authors of the system are involved in the specific representations it uses the stronger the claim that can be made about the autonomy of its associations (Hofstadter and Mitchell, 1994), and secondly it allows for the investigation of the effect of different past experiences on associations that are made, a question of interest in design research.

The system’s ability to construct its own concepts allows the object representations to include grounded typological relationships. Relationships such as “these two shapes belong to the same conceptual category” and “these two shapes belong to similar conceptual categories” arise from the system’s classification of shapes. These can then be matched to other objects containing the

same relationships. Conceptual similarity is determined by proximity in the space of possible shape descriptions. Shapes are described by their outlines, with similar outlines defining similarity and identity between shapes. This similarity is invariant to scale, rotation and position. Four shapes that belong to each of three different concepts are shown in Figure 2. Whilst the majority of these shapes are triangular (an artefact of the generation algorithm used), none of the categories are exclusively triangular, as the number of vertices is not important, only the overall outline.

The set of shapes comprising an object is then transposed into a graph-based representation in which each shape is a node, and each relationship that exists between a pair of shapes is an edge between those nodes. These edges each carry a label identifying the relationship they encode.

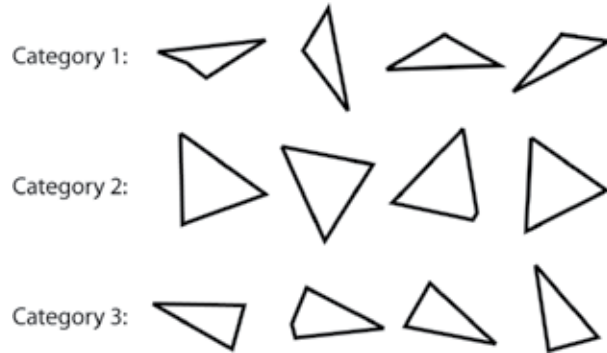


Figure 2. Three different categories of shape detected by the perception system.

The exact set of relationship types that can be used is customisable, but relationships that have been used in the system include: proximity, scale, orientation, bearing, overlap, contained within, shared vertices and shared edges, in addition to the typological relationships of similarity and sameness mentioned earlier. The relationships are expressed relatively (e.g., 'this object is half the size of that object') to aid in generalising them to other shapes.

This graph of shapes and relationships between them is then used in mapping, one graph representing the source and the other the target.

2.2. MAPPING

The mapping process finds ways in which the shapes comprising the objects share a set of relationships. That is, given that each object is represented by a set of shapes, a mapping is when some or all of the shapes within two objects have the same relationships between them in the same pattern. It is not necessary that the shapes themselves be the same, only that the relationships

between them are. In this way the mapping process of our system searches for structural rather than purely visual similarities between two objects. When a mapping is found that includes a sufficient number of shapes in both objects in a shared set of relationships, the system has constructed a new association. What portion of the shapes in an object must be included for a mapping to be sufficient is an adjustable parameter.

The mapping process searches the two graphs for sub-graph isomorphisms in which shapes are mapped by matching edges in their respective graphs. Only some relationships on an edge need be the same. A mapping that produces two pairs of shapes that both share orientation but not bearing is a successful mapping. In the absence of the interpretation mechanisms, this search can only find associations that are present in the representations constructed by the perception system. Since the relationships are stored as relative values, mappings can be made between shapes that are apparently quite different but still share a pattern of relationships.

An example of an association that can be made without any interpretation affecting the graphs is shown in Figure 3. In this association all three shapes in both object A and object B are of the same concept and share the same progression of sizes – each shape is twice the size of the one below it. This association of relative size and relative sameness can be made even though in terms of absolute size and absolute shape they are different.

When interpretation is not used the mapping algorithm attempts to match the object graphs as they have been constructed by the perception system. It is during this search that interpretation is employed to direct the search algorithm by changing the search space. The interpretation system alters the graph representations, which in turn alters both the space the mapping algorithm is searching and the course of its search. New interpretations are produced as a result of search, influence the search process and change the mapping that that process eventually produces. Without an interactive parallel model of mapping and representation, the system would be limited to associating identical (if relative) relationships like the one in Fig. 3.

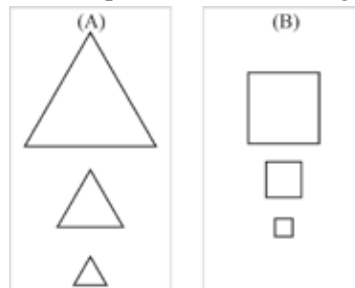


Figure 3. A simple association that can be made without an interpretation.

2.3. INTERPRETATION

Occurring concurrently with the search for a mapping between the graph representations of the objects is the model's interpretation process. Interpretation allows our model to find associations that are more abstract than when two sets of shapes share a pattern of relationships. Interpretation in association is a process that changes the representations being used. The interpretation process allows the model to find an association between two sets of different shapes that have different relationships between them, so long as the pattern of those relationships share a common structure. The system can relate, for example, a set of shapes that are all the same size to a set of shapes that are all rotated the same way, because the set of relationships between both sets of shapes shares a structure, even though they differ in content.

In this system an interpretation is defined as inducing an equivalency in meaning between one type of representation in the source and another in the target. This means that a particular edge-tag in the source graph is treated as a match with a different edge-tag in the target graph. These tags represent a pattern of relationships between shapes that exists both in the source and target objects, though neither the shapes matched nor their relationships need be literally similar.

The interpretation formation process takes potential mapping candidates from the search being performed by the mapping process and searches the node pairings they suggest for tags that do not match. If a coherent substitution of one tag in the source for another in the target would improve that randomly selected candidate mapping, the interpretation formation process suggests it as a new interpretation. Interpretations produced in this fashion are then evaluated against the current interpretation based on how many extra shapes they could match. If a new interpretation is superior to the current one by this metric it becomes the default way to view the objects and mapping proceeds under this new interpretation. This change of interpretations can only happen when the system has been unable to progress in its search for a period of time. This restriction ensures that the system is not too plastic in the adoption of different interpretations over a short period.

Through this interpretation process the system is able to make associations that are not based the existence of identical relationships in the source and target, but on shared structures of relationships that may literally be quite different. A simple form of interpretation-based association is shown in Figure 4. Here, in order to produce a mapping between the two objects, an interpretation has been constructed that treats changes in scale and orientation as equivalent. From the perspective "a change in size is the same as a change in orientation", A and B can then be associated.

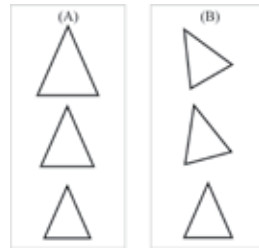


Figure 4. An association based on the interpretation '+15% scale' = '+15° orientation'.

In order to encourage diversity over multiple associations between the same two objects, the system will discard interpretations that it has used successfully many times in the past on the same association problem, as they will likely lead to solutions the system has seen before. Figure 4 represents the solution the system will find only after abandoning the default perspective and investigating other interpretations. With no interpretation the system finds that both objects in Figure 4 are groups of shapes all from the same concept. After a several runs finding the "same concepts" mapping the default null interpretation is discarded, other interpretations will replace it and the association presented in Figure 4 will be found.

This divergent behaviour expressed over many runs of the system allows multiple different associations to be found between two objects. Presenting the pair of objects in Figure 5 to the system, both the interpretations "conceptual similarity in A is the same as being from the same concept in B" and "being vertically adjacent in A is the same as sharing a vertex in B" are found. Which of these (and other) multiple possible interpretations is found by the system depends both on its history of making associations and on the direction that the mappings search process takes. The past experience possessed by the system at solving this and other, related association problems affects the interpretations and associations that the system produces.

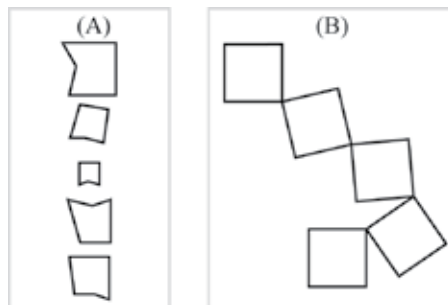


Figure 5. An association based on the interpretation 'adjacency' = 'shared vertex'.

3. Applying interpretation-driven search to a design domain

The association system presented in this paper can detect, describe, relate and categorise shapes within a design object, given only a simple vector-based representation of that object. The system can then use the higher-level representations it has constructed to find associations between objects, reinterpreting relationships within those shapes to find structures and patterns that exist in the representations of both objects. These associations, like the one in Fig. 5, may not be obvious to a human viewer. This ability is of interest to design researchers for both developing intelligent design support systems that exhibit associative reasoning themselves and in the modelling of how human designers use associative reasoning in their design process.

Systems designed to support designers through association could be of use at several points in the design process. The two design processes to which association is most applicable, as defined by the Function-Behaviour-Structure ontology of design (Gero, 1990), are *synthesis*, the creation of new design structure, and *reformulation*, the modification of design structure, behaviour or function based on existing design structure. Used to support the synthesis process an associative reasoning system would act as a form of brainstorming tool, providing a designer with new perspectives on the design problem and connections to other domains through which the design can be understood metaphorically. The association system could act as a flexible and interpretive visual index for design cases, similar to the way the Electronic Cocktail Napkin (Gross and Do, 1996) interfaced with a database of existing designs. Used to support the reformulation process an associative system could provide the ability to see new connections in the representations externalised by the designer and act as a form of artificially stimulated reflection-in-action (Schön, 1983).

Analogy making is an extension to the association process where the association is used to transfer knowledge from the domain of the source to the domain of the target. An analogy-making system based on this model of association could suggest ways to incorporate knowledge from the target domain into the designer's work based on the association that was used to retrieve a design case.

Cha and Gero (1999) describe style in architectural design as a set of relationships by which a hierarchy of visual elements are composed. Sets of shapes with consistent relationships between them form low-level patterns, and relationships between these patterns form higher-level visual structures. Examples of this relationship-based representation of style can be seen in Figure 6. The designs of Antonio Gaudí, (Figure 6a) show repetitions of similar shapes formed together into patterns (here part of an ornate grating

in the Palacio Guell and the roof of the Casa Mila). In Figure 6b the patterns are made explicit through Cha and Gero's analysis of the relationships that constitute them. An interpretation-driven visual association system would be able to associate these (and other) Gaudi designs based on their repeating elements and could be used to investigate visual style in the domain of design ornamentation.

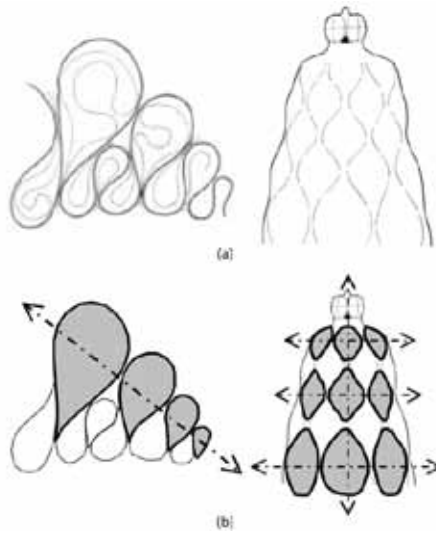


Figure 6. Buildings of Antonio Gaudi, before (a) and after (b) pattern analysis (after Cha and Gero (1999)).

4. Discussion

The representations used during design are highly mutable and the space of possible representations cannot be defined in advance. This means that in order for a computational model to operate in a design context it must be robust to this representational dynamism. Existing models of analogy and association either require unitary, fixed representations for their objects or can only operate within a precisely defined universe of discourse. These limitations hamper the applicability of these models to creative design. The model of association described in this paper builds and refines the conceptual categories used in its representations in response to its experiences, and uses reinterpretation to match between elements that were not defined *a priori* as able to be matched.

A number of extensions to the system described here could increase its capabilities. In this paper we describe a system that operates on specified pairs

of objects, it does not currently search for a source object to associate with a given target. This simplification allows us to build multiple interpretations of a single source object whilst searching for a match, rather than having to consider multiple interpretations of multiple objects. The capacity to associate a given object with any object from a library would broaden the design tasks that the system could be applied to.

The system's model of interpretation as induced equivalencies between relationships is one of many mechanisms by which reinterpretation could change representations and influence search. Other means of re-interpretation include changing the representations of different shape elements, excluding or focussing on different shapes or relationships and applying visual transformations to the source and target and re-perceiving them. Additional associations and interpretations could be modelled by constructing patterns out of the shapes the system currently uses as concepts and modelling these higher-level patterns as 'supernodes' in the object graphs.

The system we have developed demonstrates that a model of association where interpretation and mapping are parallel interactive processes is feasible. We have demonstrated that such a system can construct its own interpretations, be affected by its experiences, and be applied to visual design domains.

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EXPLOITING INSTABILITY

Reconfiguring digital systems

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Abstract. The transmission technologies of digital environments propagated by the Internet, specifically the ubiquitous webcam system, present new material to mediate people's engagement with civic space and simultaneously offer new ways to materialize its three-dimensional form. Recent research shows that the technical functionality of the webcam can be extended through deliberate intervention within the performance of contemporary camera optics. This suggests the development of new techniques for design intervention that operate in direct relationship to the evolution of the very technologies they exploit. With specific focus on the optical and chromatic translational capacities of the camera, the paper will discuss how the manipulation of its colour receptor mechanism not only provides the designer with an opportunity to exceed the constraints of commonly available colour palettes, but also it will show how this digital disruption actively capitalises upon the discrepancies that govern design strategies applied to formal production within coexistent virtual and real-time space. Through the deployment of colour filter array patterns, this new technique is able to extend the working gamut of RGB colour space in a way that allows chromatic selection for exterior and interior urban space to be linked to programmatic distribution across duplicate environments.

Keywords. CCTV; webcam; virtual; array; discrepancy.

1. Introduction

In his essay 'Scopic Regimes of Modernity', Martin Jay (1988) argues that rather than being defined by any single visual space, the contemporary visibility model comprises several simultaneously occurring and highly

competitive visual subcultures. For Jay, the coexistence of conflicting methodologies for mediating the view of habitable space to the observer is a highly productive and rewarding condition which offers a superlative platform for the generation of future visual modalities. With this in mind, a significant component of any visuality paradigm is the method according to which colour is delineated and assembled into imagistic representations of life contextualised by environment. In a contemporary frame, this chromatic delineation occurs when colour is mapped onto a discrete virtual colour space by a digital system. In accordance with Jay's observations, multiple coexistent colour spaces, working in conjunction with specific aspects of transmission technology, currently define our understanding of colour and determine its use within the public domain.

This paper will argue, despite the seeming diversity of these mechanisms for colour dissemination, that the instrumentality of chroma within the digitally transmitted image is achieved by reliance upon predetermined and stable structures. Furthermore, it will discuss how these structures exclusively support the interest of proprietary groups and marginalize individual experience. In response to this, the paper will demonstrate through a series of design-based tests that the deliberate manipulation of these digital transmission technologies allows the designer to exceed and contest any imposed viewing condition. With specific focus on the chromatic translational capacities of the webcam propagated by Internet Protocol, the paper will reveal how the manipulation of its colour receptor mechanism provides the designer with an opportunity to exceed the constraints of traditional colour palettes. Thus, through the exploitation and disruption of its own internal architecture, this digital system is able to offer the designer new opportunities for the reinterpretation and assembly of chromatic palettes that work to compose a dynamic and diverse urban space.

2. Colour space

2.1 FIXED COLOUR SPACE: PROPRIETARY COLOUR AND THE NOTION OF 'COLOUR HARMONY'

Colour software and its complementary hardware are inextricably bound into prescriptive and pre-determined relationships exemplified by the sRGB colour space, or standard RGB, created cooperatively by Hewlett-Packard and Microsoft for Internet use along with the ubiquitous Adobe RGB colour space. In these scenarios, colour palettes are accorded themes based on fixed 'harmonious' assumptions made by the software producer on behalf

of designers who work with contextual themes to achieve a particular user response to either a location or a product. An example of this is the Adobe Creative Suite and its sister site Kuler, which provide the designer with literally hundreds of thousands of predetermined Adobe colour palettes via an internal link. However, Kuler is only one of many applications that facilitate and propagate stable colour solutions to designers. Both ColorSchemer Studio and ColorImpact identify colour harmonies for the web creating palettes from photos using over a million pre-existing color schemes.

Furthermore, specific aspects of translational camera hardware such as the colour sensor mechanism also guarantee a stable and unchanging viewing experience. This mechanism acts in conjunction with software to produce design outcomes where the relationship between interior and exterior urban space becomes synthesised into an undifferentiated experience: one where design choice is imposed from without rather than being the product of autonomous decisions made by the designer in response to location, program and materiality.

2.2 UNSTABLE COLOUR SPACE

2.2.1 *Colour hardware*

The principal research strategies employed in this paper investigate the potential of the IP webcam system to facilitate the disruption of the stable and proprietary urban view that it traditionally propagates within the public domain. The strategies that arise from this investigation will therefore contribute to a broader series of productive tactics that allow the designer, through the manipulation of viewing conditions, to extend the application of working colour space in formal interventions within urban space.

The focus of this research, therefore, is the camera's colour receptor mechanism: the CCD sensor, and the colour filter array pattern located within it. The colour array is located above the pixel sensors to capture colour information and convert it to a full-colour image. The most common array is the Bayer filter with a pattern of 50% green, 25% red and 25% blue, which is used because it produces both a stable and predictable outcome and it is compatible with the numerous software applications made available for image translation. However, there are multiple alternative array assembly options within the context of an additive colour environment that have the potential to produce diverse chromatic outcomes. These patterns can be deliberately manipulated to produce both unexpected and highly strategic results that are directly linked to the visibility of anything captured within the camera's field

of view. (Figure 1)

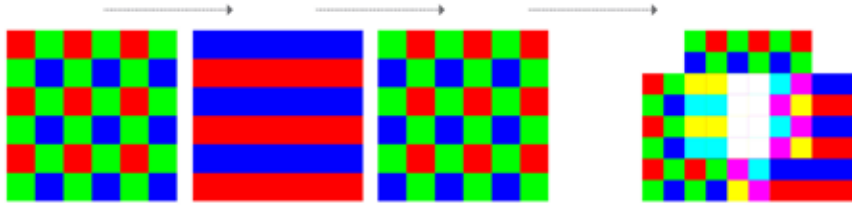


Figure 1: Bayer array pattern (left) with variations combining to produce new colour options.

2.2.2 Interference

Because the camera lens focuses the light from a single point within the image frame onto each pixel which then generates a charge proportional to that light, it follows that there is a direct relationship between the patterning within the received image and the patterning within the camera filter array. Put simply, because the charges created by the pixel array are a faithful and exact reproduction of the pattern of the transmitted image, then consequently any manipulation of pattern regardless of scale within the actual physical view will affect or disrupt its virtual counterpart.

An example of this would be the incorporation of the two complementary colours within the RGB additive colour model to the third colour at each location within the traditional Bayer pattern. In this case, the addition of red and green to blue at any location of the physical representation of the pattern [such as a building façade] would theoretically produce white or invisibility i.e. no chrominance, simply luminance when it is captured by the image sensor. (Figure 2) Similarly, the random addition of complementary colours to a third colour within the locative constraints of a specific patterning would also produce unexpected chromatic results. Thus by embedding an array pattern within the formal view, both a building's visibility and its effect are able to be strategically controlled by manipulating the relationship between its materiality and the technology that mediates it to the public. This discrepancy that is then established between the building's operation within the virtual and real environments begins not only to subvert the traditional, predictable experience of colour, but its effect also can potentially engage the viewer in a new and diverse experience of urban space.

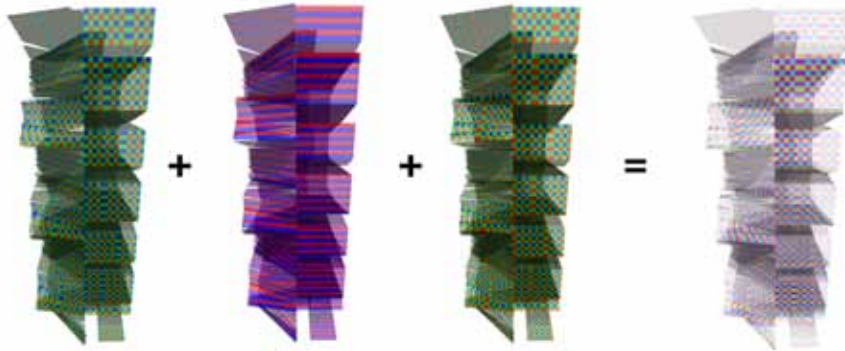


Figure 2. The strategic incorporation of complementary variants of the Bayer filter array pattern into building facades can produce both unexpected chromatic results and diminished visibility when viewed over the Internet.

3. Colour filter array tests

3.1 CONDITIONS, CONSTRAINTS AND OBJECTIVES

3.1.1 Hardware specifications and comparisons

The colour filter array tests were conducted using a Sony SX43E Handycam Digital Video Recorder. The operation of this technology is identical to that of the Sony SNC-RZ50N network camera with the exception of specific operational capacities which are detailed as follows and which were taken into account when calculating results.

Table 1. Comparative camera specifications.

	Sony SX43 Handycam	Sony SNC-RZ50N Network Camera
Sensor	CCD 1/8"	CCD 1/4"
F range	1.8 – 6.0	1.6 – 3.8
Zoom	60 x optical / 2000 digital	26 x optical / 312 digital

The camera features critical to specific tests are the zoom factor, in this case, the physical movement of the lens mechanism; the f-stop range which determines the quantity of light that can pass through the lens; and the sensor size which determines both the number and size of the pixels. For the purpose

of these tests, the network camera's lower capacity for depth of field and therefore ability to resolve image definition is offset by its larger sensor size and lower f-range which increases its ability to absorb light. Put simply, the network camera is designed for low light conditions with fewer light aberrations because of security issues, however its ability to resolve images and colours is broadly equivalent to that of the Handycam.

3.1.2 Test constraints

- Zoom factor - the test results of interest are between 1x and 26x which is the area of operational parity between the two camera mechanisms.
- Light source/aperture plane distance is at a relative scale of 1:10. i.e. a 3 metre light source/aperture plane distance in the test correlates with a 30 metre distance in an exterior environment. Likewise, the colour array patterns used are 150 x 150mm to correlate with a typical building façade element of 1.5 metres height at the same relative scale.
- The lighting source are three American DJ FS-1000 Followspots with ZB-HX600, 120V 300W Halogen Lamp.
- The tests are conducted in low ambient light conditions to simulate urban night conditions.

3.1.3 Test Objectives

Two types of tests were conducted using the Bayer array pattern and two variations of it applied as a highly translucent material to 3mm acrylic base, much the same as a theatre light gel. One of the strategies behind this selection of patterns was that when all three patterns are assembled in a direct line before a light-emitting source, each pixel component, when superimposed over its corresponding location in the successive patterns, adds to produce white light or extreme luminance. (see Figure 2) In the tests, this meant that not only could potential aberrations be observed within the performance of the individual patterns acting in conjunction with the camera lens, but when all were assembled at a specific focal length, the effect of their combined light emission should theoretically be white or zero visibility. Further to this, the addition or subtraction of one or more of these patterns then opens up the possibility of manipulating any combination to suit particular design requirements, such as the linking of programmatic arrangement with colour and its subsequent variable Internet visibility.

The second test involved the strategic location of the individual arrays in response to both camera location and angle. In this test, the patterns were each placed at a 30° angle to the camera and their collective light emission patterns

were recorded on a white board at a standard three metre distance over a range of zoom factors. The board was then replaced by the camera at precisely the point where the collective emissions of the patterns at those angles produced white. The intention was to see the result of the combination of the illuminated array patterns in relation to a range of zoom factors and also in relation to their angle of incidence to the camera lens. All test results were assembled into montages of progressive still frames using *ImageJ* non-proprietary medical imaging software.

3.2 TEST 1 – INDIVIDUAL AND ASSEMBLED ARRAY PATTERNS

3.2.1 Results

- In the individual pattern tests, in the 1-26x zoom zone, blue dominates over red in patterns 2 and 3 even though there are equal amounts of blue and red.
- This is reversed when these patterns are observed by the naked eye where red dominates over blue.
- In both the individual arrays (Figure 3) and the assembled arrays (Figure 4) an aberrant chromatic transition occurs from blue to green. This feature occurs within the zoom zone that is common to both cameras.
- This transition only occurs on the inward zoom: the phenomenon does not appear during the reverse action on the outward zoom. (Figure 4)

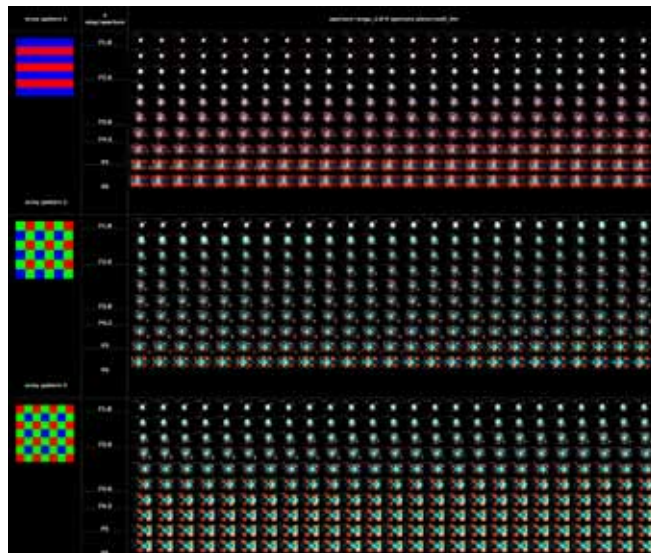


Figure 3: Individual array pattern recordings showing dominance of blue between F1.8 and F2.6 in patterns 2 and 3. Results above F3.8 lie outside the range of the network camera.

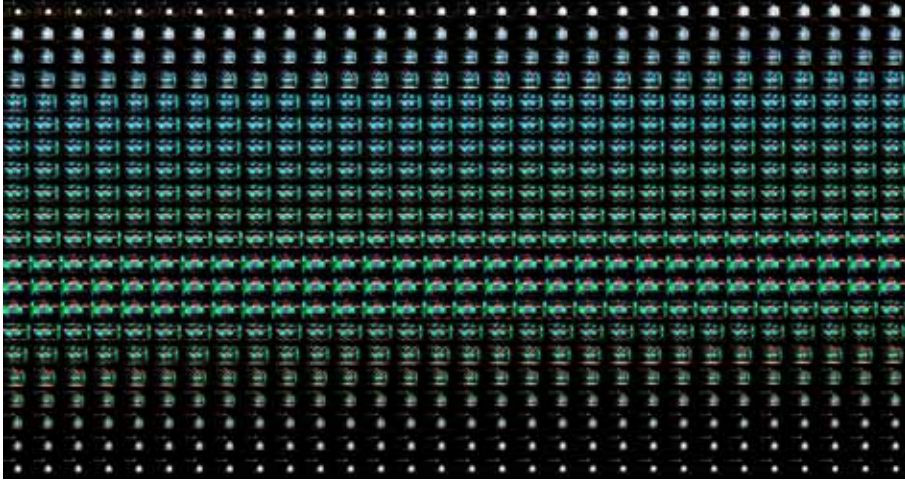


Figure 4: Assembled filter array patterns showing aberrant transition from blue to green.

3.2.2 Observations

The dominance of blue over red seen on the progressive camera images, which is the reversal of the view seen by the naked eye, opens an opportunity to control surface colour/visibility within a virtual environment and therefore to produce vast differences between the virtual and the real views. The aberrant chromatic transition which occurs in the individually recorded pattern test, and to a greater degree in the assembled pattern test, provides similar opportunities to link visibility and colour within the view to the camera's zoom function.

3. 3 TEST 2 - ARRAY PATTERN LOCATION AND ANGLE

3.3.1 Results

- When the patterns were illuminated separately on the board the pattern produced a strong effect (Figure 5).

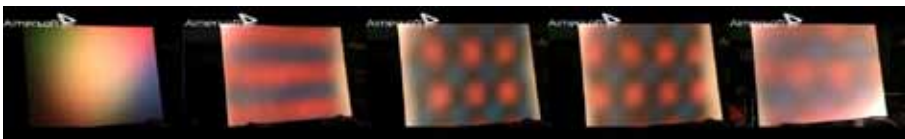


Figure 5: Far left: RGB colour emission without pattern; Centre: 3 individual pattern colour emissions; Far right: combined pattern emission showing diminished strength of colour.

- When the patterns were collectively illuminated on the board their strength began to diminish severely and approached white.
- This same effect was repeated when the camera was placed in the same location as the board. (Figure 6)



Figure 6: From left to right: zoom camera view of patterns when placed in same location as board. The image on the far left shows diminished colour to correspond with the reduced level of colour in the image on the far right of Figure 5.

- This effect this does not occur when viewed by the naked eye
- This effect only occurs at specific distance from the camera/zoom factor.

3.3.2 Observations

The combination of selected array patterns placed at a specific angle to and distance from the camera lens can produce zero chroma. This means that visibility/colour can be controlled by the deliberate selection of array patterns to interfere with the camera's receptor mechanism at pre-determined angles and distances.

4. Conclusion

The chromatic performance of the received virtual image can be controlled by strategically aligning material aspects of elements within the camera view to the camera's colour filter array pattern. This opens the possibility of linking the programmatic distribution of these elements within the image to a materiality that is determined by the designer rather than one determined by the pre-determined constraints of software and hardware. This potential orchestration of mutually informing spaces, by drawing attention to the variations and inconsistencies between the virtual and physical environments, not only extends the repertoire of design opportunities for urban intervention, but it also contributes to the experience of a contemporary habitable space that is constantly evolving and complex.

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COMPUTATIONAL METHOD FOR MAPPING QUALITY OF ARCHITECTURAL SPACE

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Abstract. The key aim of this paper is to develop a computational method for mapping architectural space used for visual openness analysis. We suggest that the result will offer possibilities for quantitative design analysis particularly on spatial quality influenced by architectural elements. The proposed method consists of two stages: determination of subdivided enclosed spaces and measuring quality using visual openness parameters on each subdivided enclosed space. We advise new approach to determine subdivided enclosed spaces on architectural plan by determining two factors: bounded space and circulation space. Computational procedures applied to analyse architectural plan and then determine map of subdivided enclosed space by analysing relationship of these two factors. The concept underlying this method is that architectural space is composed of subdivided enclosed spaces, which each of them have distinct physical properties and therefore become possible to develop mapping of evaluation regarding the quality of architectural space. Our finding on orthogonal architectural plan provides ranking index of subdivided enclosed spaces that could help for analysing spatial quality of architectural space.

Keywords. Architectural space; subdivided enclosed space; quality mapping; computational method.

1. Introduction

This study focuses on the architectural space as a result of the arrangement of architectural elements. There are two main approaches to architectural spatial modeling: One considers space we experience as a product of our perception and movement, and the other regards the space as an entity resulting from the arrangement of its boundary elements. A space as defined by later argument

is the void between physical boundaries where its existence is independent of the user's presence. Based on this principle, we further regard architectural space as a fixed entity because its basic property can be modeled and measured similar to other physical objects.

For this purpose, we develop a method for modeling subdivided enclosed space of architectural plan. Our method is derived from the following approaches: We first evaluated previous methods of computing architectural spaces and then investigated the relationships between space, circulation path and elements of architectural design. We developed new rules of application based on our findings.

2. Architectural space and the experience in the space

Architectural space is experienced not just by attributes of its boundaries. The variability in the interior (enclosed space) and exterior (enclosure) comprise the essence of architecture (Arabacioglu, 2010). Several architects (Alexander, 1977; Rasmussen, 1959; Lawson, 2001; Bentley, 1985) as well as psychologists (Shah and Miyake, 2005; Stimson, et al, 1997; Tversky, 1998, 2003) have found that the experiences in the same space can vary with the changes in architectural design elements such as colors and transparency.

Another aspect of architectural space is that architects always compose space according to the boundaries and inter-relationships between the architectural elements and planned activities. March and Steadman (1971) used network graph to denote topological relationships between rooms – which room gives access to another, which room is adjacent to another. Péna (2001) suggested that the matrix relationship of activities should be constructed to model adjacency of spaces regarding designated activities. Both studies had used basic mathematical model of spatial configuration in order to understand relationship between spatial design and activities.

Our model of enclosed spaces is the elaboration from previous study by Gross (1977), Koile (2001) and Sora (2008) with the advancement of having a map configuration of what we named as subdivided enclosed space inside a set of interior space. We believe that each area of subdivided enclosed space expresses distinct spatial qualities that are significant for spatial quality analysis and further design elaboration.

Here, we developed an elaboration model for computing architectural space quality by developing a map of subdivided enclosed space. We generated the subdivided enclosed space by analyzing two main factors: bounded area and circulation area.

3. Previous studies on spatial mapping

The concept of classification of enclosed space dates back to 1977 when M.D. Gross built a model to measure the level of spatial intensity by the number of solid boundaries (Gross, 1977). According to his study, an enclosed space is classified by adjacent walls and its numerical scale depends on the number of adjacent walls. An enclosed space can be defined by the following simple procedure: first, draw extension lines from walls, and second, construct perpendicular lines at the wall endpoints.

Koile (2001) proposed territoriality as one model for determining enclosed space in which each region is defined by its enclosure territory. Basically, the region is formed by the overlapping of territorial lines within the space. The architectural space, according to this method, is a juxtaposition of territory, circulation and use-space models; the latter is an attribute model assigned by the architect.

Through this approach, it is possible to generate an analytical model of an architectural space in which each region represents a space influenced by architectural elements.

In addition, Koile's model represents the concept of dividing the space into subsets of enclosed spaces using perpendicularly linear projections from the edges of each element. This model can accommodate solid element such as walls that form space as well as other elements such as doors that form circulation paths and spaces.

4. Subdivided enclosed spaces

In the context of architectural plan, we determined an interior space as a unit analysis. An interior space is a space comprised of enclosures, enclosed space and circulation path. We named this area as bounded area (Figure 1).

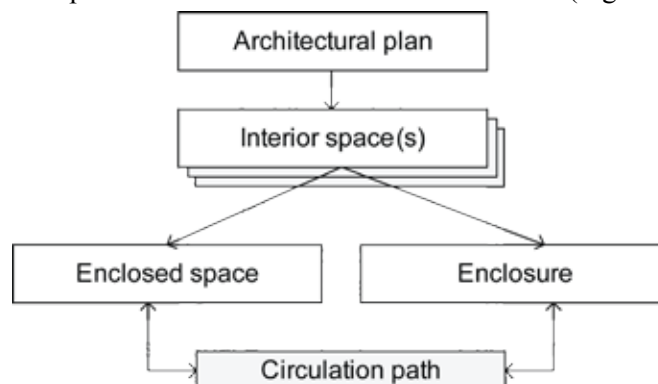


Figure 1. Unit of analysis

A bounded area comprises of rectangular-type arrangement of enclosed spaces which depend on the configuration of architectural elements at the enclosure. Our computational method is then, develop configuration of enclosed spaces based on sequential rules by considering relationship between bounded area and path. Bounded area is part of unit of analysis where enclosed spaces are to be determined. The bounded area may enclosed by opaque boundaries (walls), openings (windows or doors) and other architectural elements. A path is a circulation connector inside the bounded areas. Circulation gates such as door and path form a circulation space in the bounded area.

For determining subdivided enclosed space, Our computational method works over importer CAD data. Since the input is in polygon form, the process begins by analysing the elements of the polygon. Based on this data, program executes sequential procedures and defined rules to create layout of enclosed spaces. The sequential procedure is significant to ensure hierarchical level of enclosed spaces. At the final result, we have the bounded area which comprises of hierarchical subdivided enclosed spaces delineated by territorial lines.

4.1 METHODS AND RULES

All computational process are conducted using Grasshopper script in Rhino. Our semi-automatic method for computing subdivided enclosed spaces works in the following sequential procedures:

1. Establish L-shaped enclosed space by computing co-linearity of the boundaries and create virtual L-shaped lines to delineate the area. The co-linearity test between two polygons is performed using determinant operation by extracting maximum and minimum points of each input polygons. If determinant is not equal to zero then two polygons are not co-linear and further, program creates L-shaped area from each center point.

In example, determinant operation of three points: $P(x_p, y_p)$, $Q(x_q, y_q)$, and $Z(x_z, y_z)$ is as follows:

$$(X_p(Y_q - Y_z) - X_q(Y_p - Y_z) + X_z(Y_p - Y_q)) = 0 \quad (1)$$

2. Define horizontal and vertical axial lines based on the geometry of the bounded area and create virtual axial lines. Determination of axial lines is significant to provide guideline for next procedure. The creation of boundary polygon is necessary as an input for this procedure. Afterward, program detects its center point using this equation:

$$\text{Area of boundary}(A) = \frac{1}{2} \sum_{i=0}^{n-1} (x_i y_{i+1} - x_{i+1} y_i) \quad (2)$$

Moreover, the coordinate of the center point is as follows:

$$\text{Center } X = \frac{1}{6A} \sum_{i=0}^{n-1} (x_i y_{i+1} - x_{i+1} y_i) (x_i + x_{i+1}) \quad (3)$$

$$\text{Center } Y = \frac{1}{6A} \sum_{i=0}^{n-1} (x_i y_{i+1} - x_{i+1} y_i) (y_i + y_{i+1}) \quad (4)$$

Later, program creates line from center point perpendicular and terminates at boundary polygon.

3. Determine and create virtual extension lines from each edge of the openings and circulation path (i.e. window and door) perpendicular to each virtual axial line.

4. Divide initial enclosed space by making extension lines from the edge of L-shaped area to the nearest virtual line.

5. Establish center point of each divided enclosed space.

The result of this computational process is the configuration of subdivided enclosed spaces as illustrated in Figure 2.

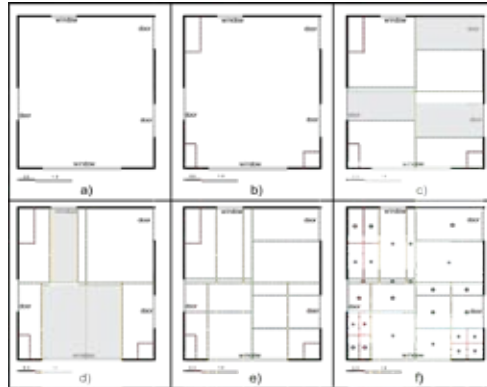


Figure 2. Graphical example of computation of subdivided enclosed space; a) Initial plan; b) Determination L-shaped enclosed space; c) Circulation area using axial line; d) Determination area of opening territory by extending its edges perpendicular to axial line; e) Determination of extended area by extending L-shaped edges perpendicular to the nearest lines; f) Center points of the subdivided enclosed spaces.

5. Model of visual openness index

Window is architectural element that provides visual, light and air connection between indoor and outdoor environment. In modeling visual openness, we consider window as the source of its influence. This visual openness influence is received by each of subdivided enclosed space we determine earlier in a different level considering their layout in a bounded area. There are three factors influence the magnitude of this influence: distance to the window, ratio of the area of the window with area of the adjacent wall and ratio of area made by a given point of subdivided enclosed space with the edges of window area and area of the bounded area. The significance of this index is that it can express the visual influence of enclosed space with such qualitative and quantitative attribute attached such as privacy, natural light and air.

5.1 METHOD

The term visual openness index refers to the level of visual influence at a reference point as result from procedural computation using three variables:

1. Visual distance; refers to the distance from a given point to the openings
2. Transparency index; refers to the ratio of opening area and adjacent wall area
3. Viewing area; refers to the ratio of area potentially seen from a given point to the window area and bounded area

As a reference point represents enclosed space area, the visual openness index expresses influence of particular architectural elements layout to the configuration of subdivided enclosed spaces. The function to model relationship of three variables is based on the exponential decay function where influence of visual connection decrease exponentially over distance:

$$VO_i = (\overline{tr})(\overline{va}_i) \exp\left(\frac{-\overline{d}_i^2}{\overline{d}_i}\right) \quad (5)$$

Where: VO_i =Visual Openness index at i ; tr = transparency index; va = viewing area index at i ; d_i =distance from i to the opening. Figure 3 illustrates this model:

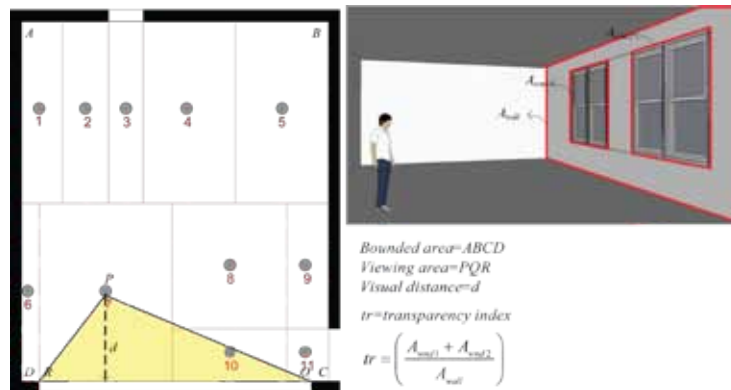


Figure3. Illustration of visual openness model of computation using three variables

6. Experiment and result

We developed procedural rules for spatial mapping and visual openness analysis using script programming in Grasshopper. The input is CAD polygon. For the experiment, we used the architectural plans of Kaufmann House (Falling Water house) by Frank Lloyd Wright (Figure3).

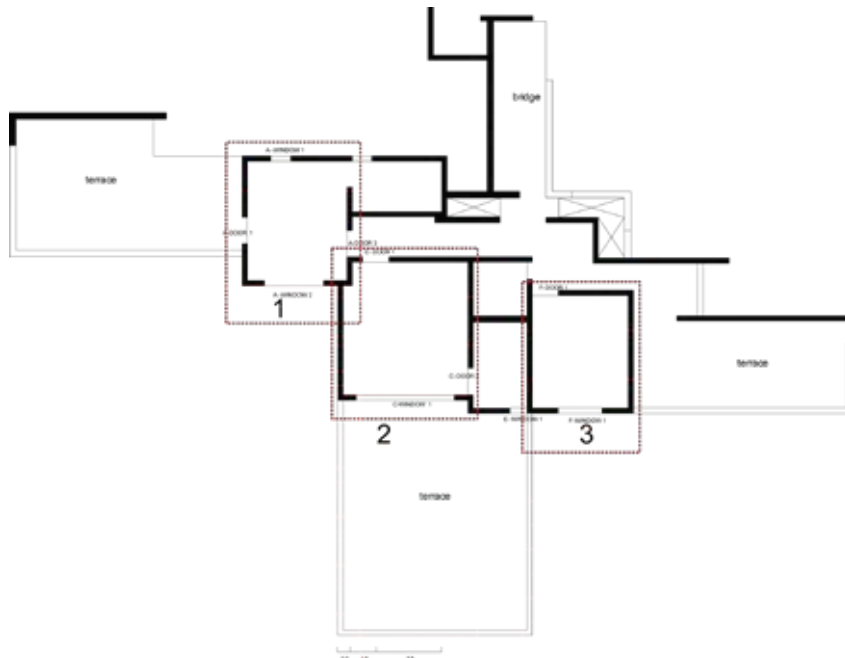


Figure 4. Kaufmann House and three areas for computational analysis

Table1 illustrates results of subdivided enclosed spaces in different interior layouts. Magenta lines indicate L-shaped area; Green lines indicate axial lines; Cyan lines indicate circulation area; and yellow lines indicate territory area.



Table 1. Procedural steps to develop map of subdivided enclosed spaces

Following this result, we conducted visual openness analysis using the formula (5). The result displayed in Figure5 and Figure6:

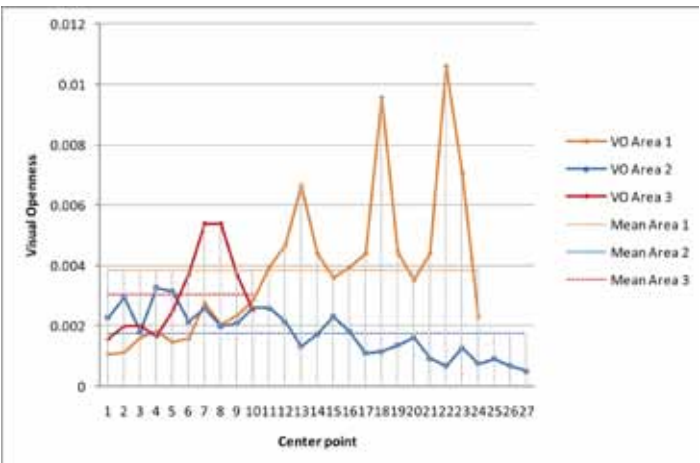


Figure 5. Diagram shows visual openness ranking of all points in three different rooms. On average, room 1 has high level of visual openness while room 2 has low level of visual openness. As a whole, all subdivided enclosed spaces in all rooms have adequate visual openness level and only about 14.4% has lowest visual openness level.



Figure 6. Level of visual openness on subdivided enclosed spaces in three different rooms (Room1, Room2 and Room3). Colour indicates level of visual openness and radius of the circle represents area of its influence in subdivided enclosed space based on minimum side of the subdivided enclosed space.

Figure 5 shows the visual openness ranking depends on the spatial configuration resulting in the quantity of its subdivided enclosed spaces and position of its subdivided enclosed space relative to the openings.

7. Summary and discussion

We presented a methodology for mapping architectural space by generating subdivided enclosed spaces. The procedures follow the below mentioned sequential rules applied to polygons of architectural plan: determination of L-shaped enclosed spaces; establishment of axial lines; determination of circulation space; and determination of subdivided enclosed space.

Generating subdivided enclosed space provides a visual cue to help designers or users develop more accurate spatial configuration. Based on this model, we develop computation of architectural space quality using visual openness as a parameter. The result on visual openness index provides an analytical cue to quantify the quality of architectural space in each area of subdivided enclosed space.

We propose that this computational design analysis will improve our understanding of organizing architectural space by a quantitative approach rather than a qualitative or subjective approach. The advancement may lead to generate a signature of an architect based on his/her spatial configuration over spatial parameters as demonstrated preliminary in this paper.

As a method to compute enclosed spaces, the proposed model has limitations that will be the focus of our future investigation. They include using

rectangular-based plan as model for analysis. We are aware that for future improvement there are some significant factors need to be addressed such as: rules for territory-based settings and elaboration on visual openness model by combining computational model with empiric-based model using human vision as well as their personality trait. The later is considered by the hypothesis that architectural space is experienced varies depends on the dominant personality trait.

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THE TERRITORY OF THE PERSONAL WORKSPACE

Development of the PWAS (Personal Workspace Analysis System)

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Abstract. The purpose of this research is to consider the behaviour of workers from the viewpoint of territory. We hypothesized that “objects on the desk show territory” from our past research. First, we developed the PWAS. This system creates a territory analytical figure from interval photography pictures. And then, experiments were carried out to consider the behaviour of workers in three different conditions. We especially focused on personal workspace, one of territory, because it is very important in considering the behaviour of workers. From this research, we obtained several suggestions regarding the determinant of personal workspace in the office and the influence which physical environment has on personal workspace. From the above, this research shows that territory is very important to understand the behaviour of workers. In addition, it is meaningful that the appraisal techniques using the PWAS obtains these result to some extent.

Keywords. Office; territory; personal workspace; analysis system; behaviour monitoring.

1. Introduction

In this paper, we argue that it is necessary to account for human behaviour and

to reflect such data into design. This paper proposes to introduce computer monitoring and analysis of behaviour for this purpose. We specifically consider the behaviour of workers from the viewpoint of territory and examine personal space which is considered to have a major impact on workers' behaviour. Territory is an important factor in understanding the behaviour of workers that has however not received much attention in the field of office research as yet. The two reasons for this are as follows; 1) It is difficult to quantify related data, 2) territory is often seen as having no influence on behaviour. Furthermore, importance of territory has increased in non-territorial offices that are becoming more common. This is because in non-territorial offices¹, a major factor in determining workers' comfort in the office is whether they can adjust their personal space appropriately or not. Based on a previous study, we hypothesize that objects on the desk show territory. First, we develop the PWAS (personal workspace analysis system). And then, experiments are carried out to consider the behaviour of workers in three different conditions. We especially focused on personal workspace, one of territory, because personal workspace is very important in considering the behaviour of workers.

1.1. PREVIOUS RESEARCH

There have been many studies of image processing, including (Iso, 2007), but the means for analyzing territory of the desk in the office has not been made clear. One of the previous studies that analyzed the monitoring of behaviour with image processing is (Konno, 2007). Konno showed that one of the problems in image processing is with the depth judgment and graphic mode of the camera. Monitoring behaviour in the office by image processing is difficult. Therefore, in this study we fixed the camera on to the top of our developed desk system and analyzed territory on the desk in the vertical position. In addition, by applying previous research we found a new analytical method that specializes in analysis of territory on the desk.

2. Establishing of the experimental environment

This paper was guided by the following four points (Table 1), and the experimental environment was constructed accordingly to observe the personal workspace.

Table 1. Guideline and contents for the establishment of the experimental environment.

guideline	contents
Establishment of experimental environment that reflects the current state of the office	Selection of furniture to meet the needs of the times
Using the furniture that we can observe the territory	Producing desk-systems to share a desk surface / Use of free address desk
Development of methods for observing personal workspace	Development of a system that simplified the data in a variety of personal workspaces
Efficiency for the office observation	Development of a system using image analysis process that observes office

2.1. DEVELOPMENT OF THE PWAS (PERSONAL WORKSPACE ANALYSIS SYSTEM)

In order to understand personal workspace dynamics, we developed the PWAS as shown in Figure 1. The PWAS allows for 1) monitoring of the physical layout of the overall personal workspace, 2) observing the behaviour of workers in the office more efficiently, that is the PWAS obtains reproducible results in as little time as possible.

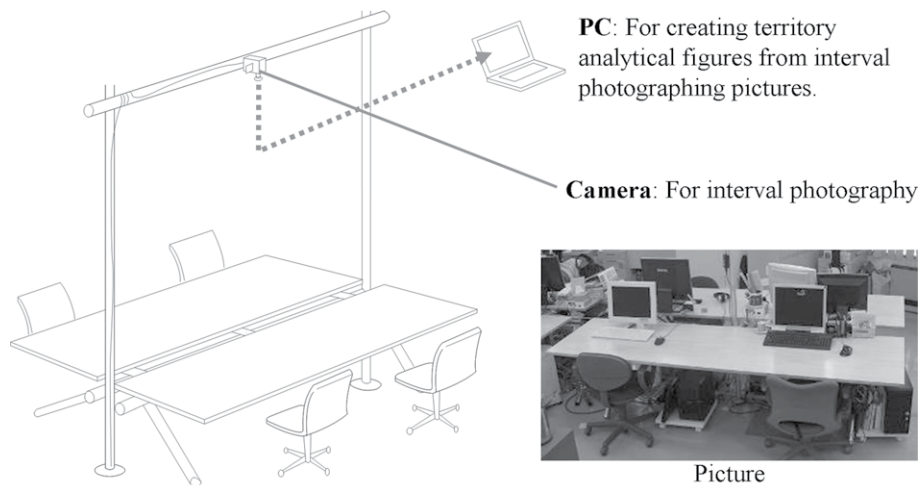


Figure 1. Summary of the PWAS.

The PWAS system creates an analytical figure of territory from interval photography in the following process illustrated in figure 2.

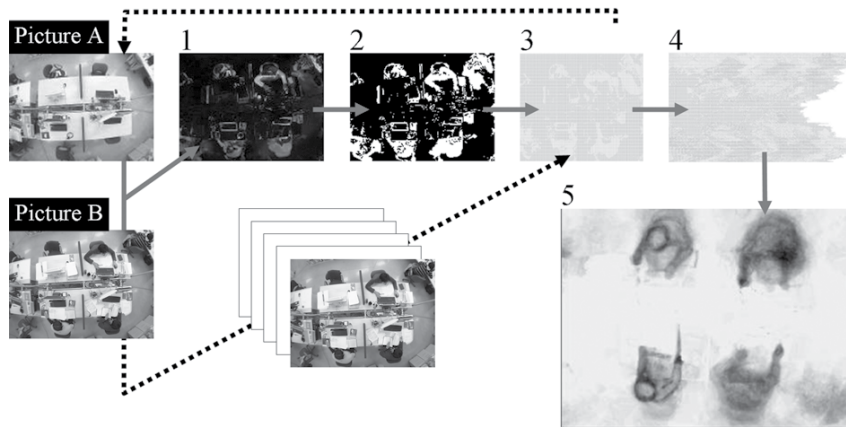


Figure 2. Process of creating the territory analytical figure.

- **1:** Calculating an absolute difference between Picture A and Picture B.
- **2:** Creating a black and white mask image by extracting differences between Picture A and Picture B.
- **3:** Converting the above mask image into the partial-array; different pixels are 1, same pixels are 0.
- **4:** Repeating 1 2 3 process for all interval photography pictures. And this system creates the total-array that composes all partial-arrays.
- **5:** Generating the territory analytical figure, like a thermograph, from the total-array.

2.2. THREE TYPES OF TERRITORY ANALYTICAL FIGURES

Table 2. Explanation of territory analytical figures.

Whole territory analytical figure	Worker's territory analytical figure	Object's territory analytical figure
Whole territory where it was occupied by workers and objects is displayed. (Calculates absolute difference with an initial image.)	The territory where workers used frequently is displayed clearly. (Calculates absolute difference with a previous image.)	The territory where objects were placed is displayed clearly. (Calculates absolute difference between Whole territory analytical figure and Worker's territory analytical figure.)

This system compares each interval photography picture with an initial image and a previous image to observe the personal workspace from various view-points, creating three kinds of territory analytical figures as shown in Table 2.

2.3. DEVELOPMENT OF A SINGLE-LUMEN DESK SYSTEM

We developed a “single-lumen desk system” (Figure 3) that is shared by four people, as the experimental environment to observe personal workspace. In developing system we aimed to clearly observe territorial behaviour from a desk system in which workers share desk surfaces and establish an experimental environment that reflects the typical office environments.

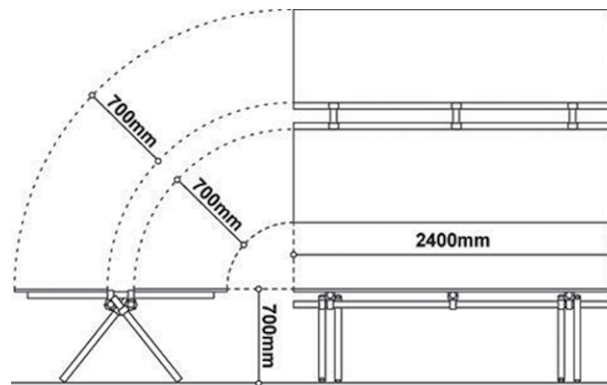


Figure 3. Three-sided drawing of a single-lumen desk system.

3. Experiment

We did three types of personal workspace observation experiment using this system (Table 3); Type A: no partition and individual dedicated seats, Type B: with partition and individual dedicated seats, Type C: no partition and free-address seats. Each experiment was carried out for 6 hours (2h*3). We photographed every one-minute and got 1080 pictures in the 18 hours from all experiments.

Examinees were four members² of our laboratory who worked on some practical projects and research. Territory analytical figures were created from the picture group of each experiment (2h., 120 pictures). We analyzed these from the viewpoint of the position of objects and the position of workers.

Table 3. Summary of the applied experiment.

Number of subjects	4	Test duration	2hour*3set
Type A	Type B	Type C	
Fixed address / No partition / Desktop PC	Fixed address / With partition / Desktop PC	Free address / No partition / Laptop PC	
			
The determinants of the personal workspace in uncertain boundaries	The impact of clear boundary on the personal workspace	The characteristics of the personal workspace in non-territorial	

3.1. ANALYSIS AND CONSIDERATIONS

We analyzed the territory analytical figures obtained in the experiment by visual judgment, with special regard to:

- The position of objects (Table 2: Object's territory analytical figure)
- The position of workers (Table 2: Worker's territory analytical figure)

3.1.1. The position of objects

Type A: We observed characteristic areas indicated by the dotted line in figure 4. These are typical areas which are hardly used between workers of the next seat. We presume that these areas form buffer zones that adjust the balance of privacy and communication.

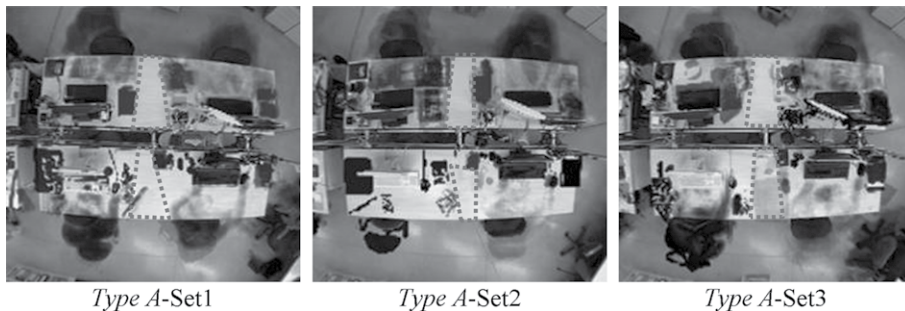


Figure 4. Object's territory analytical figure group that was provided from the Type A experiment.

Type B: We observed the characteristic behaviour of the workers in the areas indicated by the dotted line in Figure 5. In these areas, workers place objects beside the partition. This behaviour shows that physical environment is modified through workers personalising their territory.



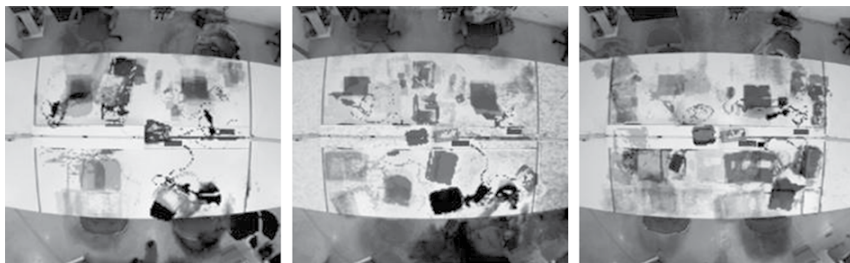
Type B-Set1

Type B-Set2

Type B-Set3

Figure 5. Object's territory analytical figure group that was provided from the Type B experiment.

Type C: We observed the characteristic behaviour that was not seen in the individual dedicated seat experiments of this experiment (figure 6). As for the individual dedicated seats, the static territory and the dynamic territory are divided clearly, but the position of the objects on the desk with free-address seats always changed.



Type C-Set1

Type C-Set2

Type C-Set3

Figure 6. Object's territory analytical figure group that was provided from the Type C experiment.

3.1.2. The position of workers

The position of the workers is not so different between Type A and B. But comparing the individual dedicated seats (figure 7) with free-address seats (figure 8), workers frequently changed their position with free-address seats. This is because workers used laptop PCs with free-address seats (Type C). This suggests that the form of the PC influences the position of workers.

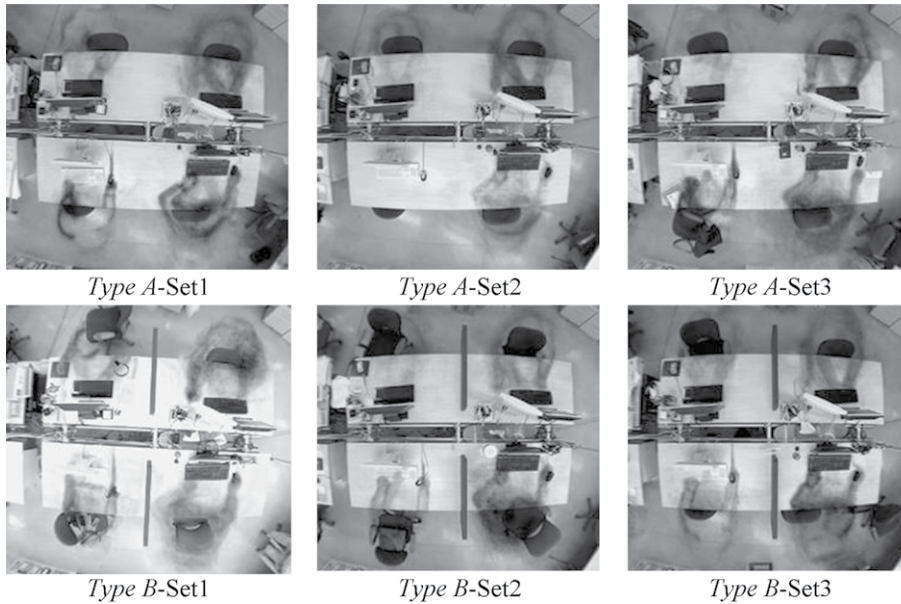


Figure 7. Worker's territory analytical figure group that was provided from the individual dedicated seats experiments.

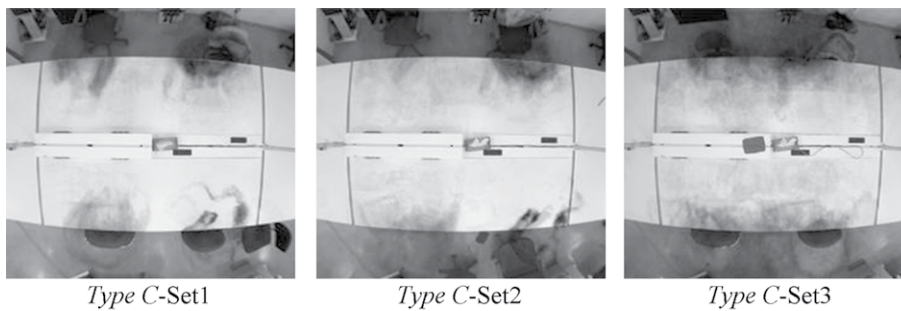


Figure 8. Worker's territory analytical figure group that was provided from the free-address seats experiments.

3.2. EXPERIMENT SUMMARY

The following summarizes findings from the three experiments in this study:

- The boundary of each other's workspace is not clear (Type A). Workers tend to establish buffer zones near personal workspace boundaries.
- The boundary of each other's occupied space is clear (Type B). The workers tend to form their territory based on its borders.

- Comparing Type C with Type A and Type B, Type C sees dynamic expansion.
- Comparing Type C with Type A and Type B, Type C has greatly changed the worker's position.

From these findings, the layout of personal workspace in offices was confirmed to have a considerable impact on the use of physical environment. At the same time, institutional differences, such as individual dedicated seats or free-address seats, seem to affect personal workspace in the office. In particular, the results of Type C suggest that workers try to adjust their environment by constantly changing their territory.

4. Future works

Future work will address the following three points: 1) Expanding the scope of observation, 2) Studying psychological factors, 3) Further developing functionality of the PWAS. Future prospects include converting new knowledge about the personal workers' territory in the office into designing. If the PWAS allows for more efficient observations, observational surveys of office spaces over long periods become possible.

5. Conclusion

In this study, we observed the environment of the office desk from the perspective of territory. The major theme was to clarify the impact of territory on the behavioural characteristics of workers. From previous research on territory and our past research, we concluded that 1) Individual territory has been overlooked in the office, and 2) Individual territorial behaviour will become a relevant factor in office layout in the future. From this research, we obtained several suggestions regarding the determinative factor of personal workspace in the office and the influence which the physical environment gives to personal workspace. Two findings are shown below.

- How to divide the territory of workers that has a great influence on personal workspace.
- When free-address seats and individual dedicated seats are compared, the territory of free-address seats is more dynamic and expandable.

From the above points, this research shows that territory is very important to understand the behaviour of workers. In addition, it is meaningful that we developed the new appraisal technique using the PWAS. In this paper, we tried quick and simple experiments. The PWAS should be improved and the system should be repeatedly tested in various cases, utilizing the features of the system, so that it can analyze vast amounts of data for a long time easily

and quickly, albeit a rough analysis.

Endnotes

1. The non-territorial office is one of the office forms. Multiple employees share the desk, equipment and space in the office.
2. The subject information; Type A: Clockwise from top left in picture of Table 3; Male worker (22), male worker (24), male worker (24), female worker (22), Type B: Same as above, Type C: Clockwise from top left in picture of Table 3; Male worker (25), female worker (23), female worker (21), male worker (26)
All are students. They knew they were being observed. They were engaged in individual research and projects. They did not collaborate with each other at their desks during the experiments.

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DATA FLOW AND PROCESSING IN THE COMPUTATIONAL FRACTAL ANALYSIS METHOD

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Abstract. One of the few quantitative methods available for the consistent analysis of architectural form is the ‘box-counting’ approach to determining the approximate fractal dimension of a plan or elevation. In its computational form this method has been used to analyze the plans and facades of a wide range of buildings. The data points produced are synthesized by the software into a series of fractal dimension (D) values that are in turn compiled in various ways to produce a series of composite results describing a complete building. Once this process is complete the data may be coded with additional information producing a set of mathematical results that describe the form of a building. This paper offers the first complete description of this important analytical process from the point of view of information flow, algorithmic operations, review options and data magnitude. No previous paper has detailed the full scope of the data used in the computational method, or the way in which various stages produce different types of outcomes. The purpose of this paper is to elucidate the way in which this particular computational method, drawing its inspiration from the complexity in natural systems, may be used to process different types of information and produce various forms of quantitative data to support architectural design and analysis.

Keywords. Fractal analysis; computational analysis.

1. Introduction

There are relatively few methods available to support the consistent and quantifiable analysis of architectural form. While a small number have been pro-

posed over the last few decades (Krampen, 1979; Stamps III, 1999) only one, the fractal analysis method, has been adopted by a wide range of scholars and has been applied in more than 50 cases. There are two related versions of this analytical approach both of which share a common algorithmic core. The first, the “manual method” (Bovill, 1996; 1997) which is produced by hand on transparent overlays, identifies a limited range of results for an isolated image. The second method, the “computational” variation (Ostwald, Vaughan, Tucker, 2008; Ostwald and Vaughan, 2009a) produces an individual result for an image from a comprehensive review of the information present in a plan or elevation. These results can then be combined together in various ways to analyze complete buildings or sets of works. While there are several other variations which merge aspects or qualities of the two (Lorenz, 2003) these remain the most widely published methods. However, despite their relatively widespread application, a detailed account of the computational process which underpins them – from the point of view of the type of information required, its method of processing and its output forms – has never been published. In response to this situation, the present paper provides a brief overview of the theory and background to fractal analysis, before developing a detailed, information-based account of the operations in the computational variation. This description not only charts the influence of several limitations in the process, it identifies the scale and complexity of the data present in different stages and during key operations in the process.

2. Background

Fractal geometry may be used to describe irregular or complex lines, planes and volumes that exist between whole number integer dimensions. This implies that, instead of having a dimension, or D , of 1, 2 or 3, fractals might have a D of 1.51, 1.93 or 2.74 (Mandelbrot, 1982). There are a range of methods for determining the approximate fractal dimension of an object and one of the most common, the box-counting approach, was developed by Bovill (1996; 1997) for the analysis of architecture. Bovill’s work demonstrated that the fractal dimensions of line drawings of elevations of different buildings could be determined using this approach. In the last 15 years the manual variation of this method has been widely used for the analysis of architectural and urban designs (Bechhoefer and Appleby, 1997; Makhzoumi and Pungetti, 1999; Burkle-Elizondo, Sala and Valdez-Cepeda, 2004). Ostwald, Vaughan and Tucker (2008) developed a computational variation of this method which has since been consistently applied to the analysis of more than 40 famous designs by a wide range of architects including Frank Lloyd Wright, Eileen Gray, Peter Eisenman and Kazuyo Sejima (Ostwald and Vaughan, 2009a; 2009b; Vaughan

and Ostwald, 2009).

3. Computational fractal analysis method

The computational fractal analysis method may be visualized as a process diagram delineated by four types of information flows or states (inputs, processes, operations and outputs) (see Figure 1). The procedure itself occurs over two, three or four stages, depending on the type of results required. Thus, for example, at each of the three main procedural stages {1.0, 2.0, 3.0} there is an opportunity to generate different types of results {1.4, 2.2, 3.3}.

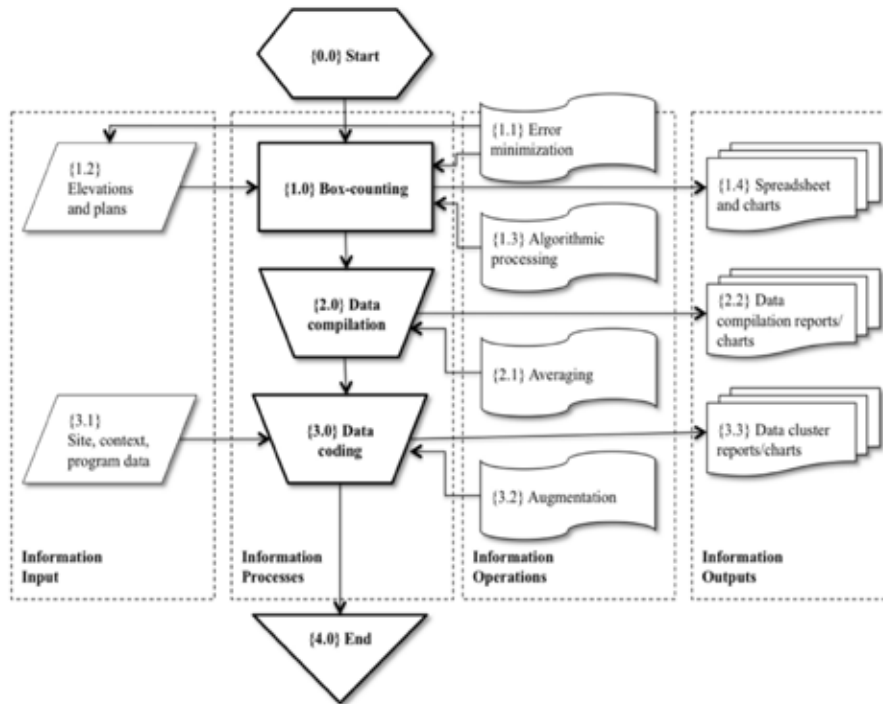


Figure 1. Computational Fractal Analysis process flow chart.

The first stage {1.0} in the process involves the application of the box-counting procedure to a selected image (input data). However, before this has even occurred there is a critical error minimization process {1.1}. The fractal analysis method has several known limitations that can cause errors in the results. The four common problems with the method are associated with balancing “white space” and “starting image” proportion, line width, scaling coefficient and moderating statistically divergent results (Lorenz, 2003, Foroutan-Pour,

Dutilleul and Smith, 1999; Ostwald and Vaughan, 2009a). No single solution exists to these problems but by closely controlling the quality of the input data (plans and elevations) and by consistently applying these rules, three of the four limitations are minimized to such an extent that they have little or no impact on the results. In practice, this means that the input data frequently has to be redrawn or reconstructed using the same graphic conventions for all images to ensure that the results are accurate and consistent. The impact of the fourth limitation, statistical divergence, is currently checked after the box counting stage to see if it is significant {1.1}. If it is significant, it is possible to manually adjust the number of grids used for the comparison to ensure that the results are valid.

The box counting procedure {1.0} may be undertaken either by specially authored software (*Archimage*) or commercial software (*Be-noit*) or a combination of both. In each case, the software uploads the input data {1.2}, which is usually a plan or elevation of a building. A grid is then placed over the drawing and each box in the grid is analysed to determine whether any lines from the façade are present in it (see Figure 2). Those grid boxes that have some detail in them are then marked. This data is then processed {1.3} using the following numerical values:

$s^{(s)}$	=	the size of each box in the grid
$N^{(s)}$	=	the number of boxes containing some detail
$1/s$	=	is the number of boxes at the base of the grid

Next, a grid of smaller scale is placed over the same façade and the same determination is made of whether detail is present in the boxes of the grid. A comparison is then made of the number of boxes with detail in the first grid ($N_{(s1)}$) and the number of boxes with detail in the second grid ($N_{(s2)}$). Such a comparison is made by plotting a log-log diagram ($\log[N_{(s)}]$ versus $\log[1/s]$) for each grid size. This leads to the production of an estimate of the fractal dimension of the façade; actually it is an estimate of the box-counting dimension (D_b) which is sufficiently similar that most researchers don't differentiate between the two. The slope of the line (D_b) is given by the following formula:

$$D_b = \frac{[\log(N_{(s2)}) - \log(N_{(s1)})]}{[\log(1/s2) - \log(1/s1)]}$$

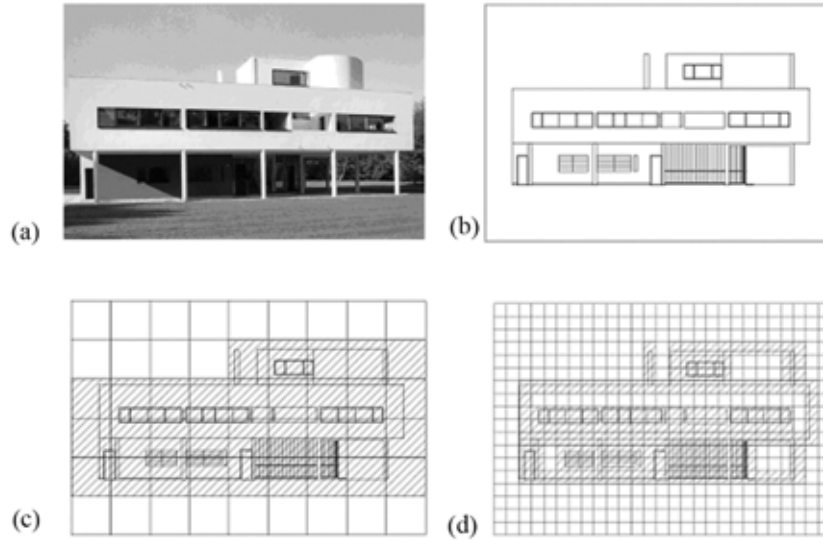


Figure 2. Example of the start of the box-counting approach (a) Villa Savoye, (b) façade elevation, (c) stage 1, grid, (d) stage 2 grid.

For the analysis of a house, say Le Corbusier's Villa Savoye, each elevation will require around 13 or 14 iterations (grid comparisons) to produce a reasonable result whereas for a large historic building (say the gothic revival British Houses of Parliament) over 100 grid comparisons may be needed for each façade. Once this is complete, a spreadsheet is then automatically produced (see Table 1) containing all of the collected data on the elevation or plan. In the example, Table 1, the smallest grid size used for the analysis was 5 pixel boxes, and there were 5583 of the boxes in this grid size containing data. The largest grid size was 425 pixel boxes, and there were only 6 data points found in this grid. The results in the table are then charted in a log-log scale producing the fractal dimension results D (see Figure 3) $\{1.4\}$.

Table 1. Example results for box-counting the Villa Savoye façade: $D_{(Elev)} = 1.441$.

Iteration	Box Size	Box Count	Iteration	Box Size	Box Count	Iteration	Box Size	Box Count
1	5	5583	6	27	610	11	150	53
2	7	3681	7	38	379	12	213	29
3	9	2605	8	53	234	13	301	16
4	13	1539	9	75	157	14	425	6
5	19	955	10	106	82	-		

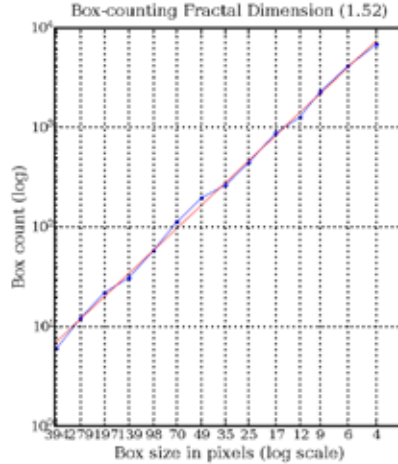


Figure 3. Example Log-Log diagram for the Villa Savoye façade: $D_{(Elev)} = 1.441$.

The following stage {2.0} of the procedure is concerned within taking isolated D results for an individual elevation (or plan) and combining them to produce a set of average or typical fractal results which reflect characteristic levels of two dimensional visual complexity in a complete design. In the first part of this process each elevation is analysed using *Archimage* and *Benoit* programs producing, respectively, a $D_{(Archi)}$ and a $D_{(Benoit)}$ outcome. Then, the $D_{(Archi)}$ and $D_{(Benoit)}$ results for each elevation are averaged together to produce a separate $D_{(Elev)}$ result which moderates the different software packages respective tendencies to under-count or over-count detail.

For a typical house elevation, this $D_{(Elev)}$ result represents a summary of more than 26 separate mathematical comparisons each of around 7,000 data points, and using two variations on the box-counting approach (*Archimage* and *Benoit*) to produce an optimal result {1.3 & 2.1}. Next, the $D_{(Elev)}$ results for each of the four elevations of a building are averaged together producing a $D_{(Comp\ Elev)}$ result; being the average, two dimensional visual complexity of a complete dwelling as represented by its elevations {2.1}. This $D_{(Comp\ Elev)}$ result is typically the culmination of over 100 calculations and 28,000 automated data detection decisions.

The same procedure is then repeated for the plans of the building, initially producing a $D_{(Plan)}$ result for each level that is then combined into a $D_{(Comp\ Plan)}$ outcome. Finally, the $D_{(Comp\ Plan)}$ and $D_{(Comp\ Elev)}$ results may be averaged to create a single $D_{(Comp\ Plan + Elev)}$ result which is the best reflection of the two dimensional formal and spatial characteristic visual complexity of a building (see Figure 4). Each of these three forms of output, $D_{(Comp\ Plan)}$, $D_{(Comp\ Elev)}$ and

$D_{(\text{Comp Plan} + \text{Elev})}$ may be reported at this stage if required {2.2}; alternatively, this stage {2.0} can end with the production of the $D_{(\text{Elev})}$ results which are coded {3.0} in the final stage of the process.

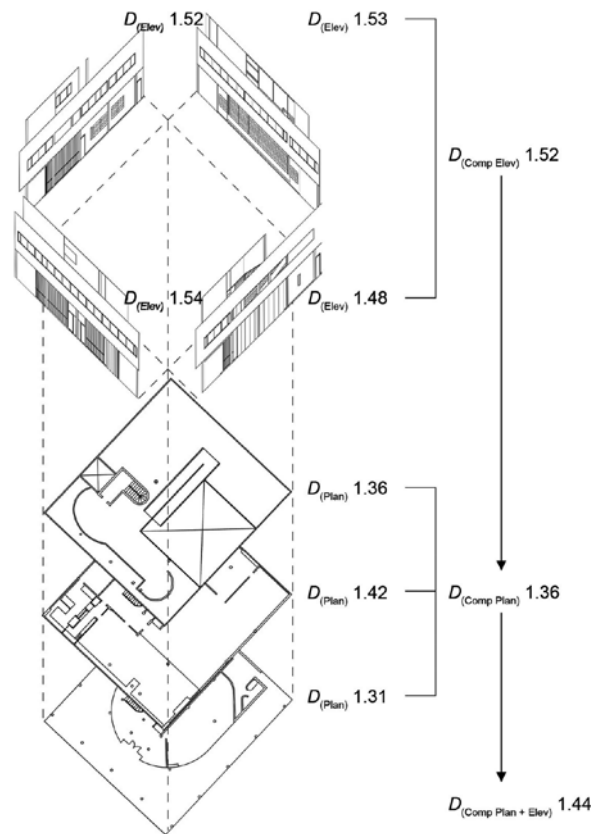


Figure 4. Diagrammatic representation of the "data compilation" stage {2.0}.

One of the practical challenges with applying the data developed from the computational fractal method is that it produces a single numerical result for each case being considered. This means that the data is in the form of isolated numbers on a linear scale and within a fixed range ($2.00 > D > 1.00$). This is akin to producing a chart which has a single "x axis" along which points are placed. The application of this type of data is essentially limited to comparisons between, for example, buildings that have higher levels of complexity and those that have lower levels. Or alternatively, this data can be used for comparisons between different architects' works or different periods in an architect's body of work. While such comparisons have been used to confirm

a range of intuitive readings of architectural form, the application of fractal analysis is limited without its augmentation with an additional dimension; in effect, producing a “y axis” to compliment the current, isolated, “x axis”. This is why the manual coding {3.0} of fractal data is so important.

The four current reports {3.3} that can be generated from the coding stage {3.0} are concerned with, respectively, orientation on site, approach to the building, permeability (the number of windows in each façade) and program (a variation of permeability which requires the programmatic function associated with an opening to be charted against the number of windows). In each case, the process uses additional information in the form of site plans, annotated floor plans and the expertise to read and interpret them {3.1}. In this way each $D_{(Elev)}$ result may be coded to reflect up to 8 different qualities of orientation and approach, and a wide range of permeability and program results {3.2} (see Table 2). The typical outcome of this final stage is a set of graphs or charts comparing the relative visual complexity of a façade and its architect’s design strategies for sitting, address and program {3.3} (see Figure 5).

Table 2. Example coding of $D_{(Elev)}$ data for the Villa Savoye against three criteria

House: Villa Savoye	D(Elev)	Orientation	Approach	Permeability
Elevation 1	1.512	N	F	27
Elevation 2	1.4855	E	L	21
Elevation 3	1.5175	S	B	17
Elevation 4	1.450	W	R	12

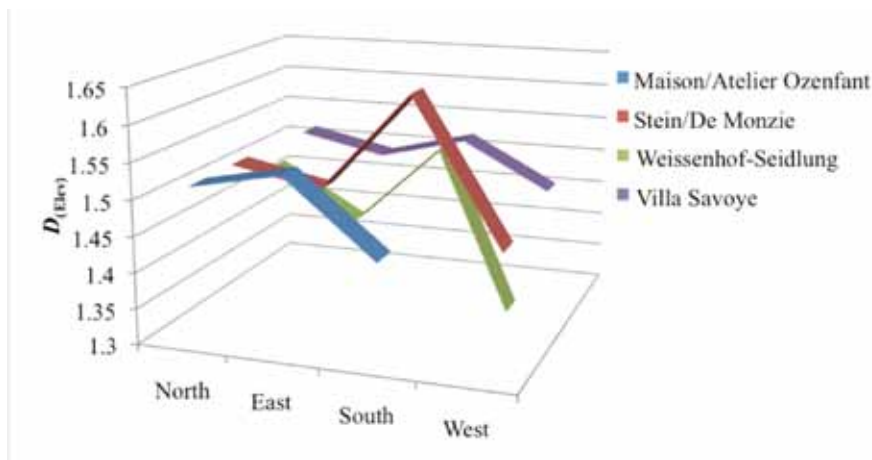


Figure 5. Example $D_{(Elev)}$ results for the Villa Savoye charted by orientation against the same results for three other houses by Le Corbusier.

4. Conclusions

The scientist Mandelbrot (1983) famously developed his system of non-Euclidean geometry in response to an observation that natural systems had a degree of complexity that defied conventional analytical techniques. However, with the rise of the computer, complex processes could suddenly be modelled for the first time. As a result of this, the architectural community now has access to a technique for analyzing the full complexity of architectural form and an appropriate set of computational tools for dealing with the large amounts of data they produce. Nevertheless, while computers may enable this process to occur, it is critical for researchers, scholars and designers to understand how this method works. This is why the present paper sets out to both trace and explain the processes that make up this important analytical method and the different forms of output it is capable of producing.

In the case of the example used throughout this paper, the Villa Savoye, the computational fractal analysis technique commenced with seven initial pieces of information (three plans and four elevations) from which it identified almost 42,000 relevant data points which were processed through around 182 iterative mathematical comparisons. This data was then synthesized to produce 10 results; $4 \times D_{(\text{Elev})}$, $3 \times D_{(\text{Plan})}$ results, $1 \times D_{(\text{Comp Elev})}$, $1 \times D_{(\text{Comp Plan})}$ and $1 D_{(\text{Comp Elev + Plan})}$. The $4 \times D_{(\text{Elev})}$ results were then coded against 8 closed variables (that is, variables with a fixed range) and two open variables leading to more than 40 critical comparison points for the complete house. While the Villa Savoye is a relatively small house, the present authors have used the computational technique to begin to analyze a major historic building and in doing so they produced more than 2 million data points from over 1000 mathematical operations; the scale of the information processing required exceeded the capacity of the average desktop computer and required extensive dedicated processing time to complete. As the method is increasingly applied to more complex cases it becomes even more important that the people using or considering using this method are aware of its methodological and conceptual strengths and limitations. This paper provides the background for this knowledge, and further research will provide a critical assessment of the fractal analysis of architecture.

Acknowledgements

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COMPUTATIONAL DESIGN ANALYSIS II

48. Digital forensics as a tool for augmenting historical architectural analysis: Case study: The student work of James Stirling 505
Nicholas Webb and Andrew Brown
49. Towards morphogenetic assemblies: Evolving performance within component-based structures 515
Daniel Richards
50. Closing the loop of design and analysis: Parametric modelling tools for early decision support 525
Bianca Toth, Flora Dilys Salim, Robin Drogemuller, John H. Frazer and Jane Burry
51. Topology pattern mining: A visual approach for representing and retrieving design patterns of spatial topology in a case library 535
Chieh-Jen Lin
52. Assessing innovation in hybrid designs using shape grammars 545
Dhuha A. Al-Kazzaz and Alan Bridges
53. Agent-agent interaction as a component of agent-environment interaction in the modelling and analysis of pedestrian visual behaviour 555
Arash Jalalian, Stephan K. Chalup and Michael J. Ostwald

DIGITAL FORENSICS AS A TOOL FOR AUGMENTING HISTORICAL ARCHITECTURAL ANALYSIS

Case Study: The student work of James Stirling

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Abstract. Digital techniques in architecture have developed rapidly over the last 25 years. This has enabled digitally mediated visualisations to become increasingly complex, and potentially more beneficial to the user. In architectural critique this creates an opportunity to re-analyse and re-interpret paper and photographic records of architectural artefacts. The information available to construct models of lost or unbuilt designs is almost always incomplete; therefore interpretation of material requires parallel study into the architect, their influences and the contemporary context they operated within. This can prove to be a rich exercise in augmenting a critical architectural analysis of an architect, a built product or building type. The process of constructing a model and its subsequent analysis can be referred to as scenario building, or informed extrapolation. This paper uses the reconstruction of an unbuilt scheme by Sir James Stirling as a vehicle to explore and illustrate the techniques, implications and limitations of the process.

Keywords. Forensic analysis; digital modelling; scenario building; virtual reconstruction.

1. Introduction

The idea of digital recreation of unbuilt or lost architectural artefacts has been an area of interest since the time when reasonable quality digital visualisations of architectural models could be produced. In the 1990s and subsequently work such as that of Burry and Burry (2006) in relation to Temple Sagrada Familia in Barcelona has by necessity used techniques in which the digital representation has enabled appropriately informed construction of the unbuilt.

There are those who question the appropriateness of reconstruction, or construction of the unbuilt, such as Jarzombek (2004). But such debates are an inevitable part of the most engaging aspects of Architectural critique. When Architecture stops creating debate it stops being Architecture.

The study reported here is part of a larger research investigation into a series of architects and their work. The concern here is to help better understand the early formative years in James Stirling's career, from the time when he was a student at the Liverpool School of Architecture.

2. Case study overview

In 2008, Liverpool celebrated its year as European Capital of Culture and as part of the events held across the city, the Liverpool School of Architecture launched an exhibition and catalogue entitled 'The World in One School'. The catalogue focuses on outstanding alumni from the school and notes the six Royal Gold Medallists for architecture amongst the former staff and students (Dunne and Richmond 2008). One of the former students to achieve this outstanding recognition was Sir James Stirling (1926-1992).

Stirling is one of the school's most successful graduates and his work holds significant influence and admiration amongst the architectural community (Jacobus 1975; Rowe 1984). In order to enhance our understanding of Stirling's architecture the decision was taken to reconstruct the lost model of his final thesis project of a community centre at Newton Aycliffe designed in 1950. All that remained in the University of Liverpool archives were photographs of the original model constructed at a small scale and an incomplete set of drawings. However, it soon became apparent that the information available to build the model was fragmented. Therefore, the task involved piecing together the available information and working out how to interpolate and extrapolate to fill in the missing elements of the design. Stirling's education and early work as an architect was studied in order to understand his design principles and realise the context the thesis project was set in. This paper describes the process of investigating fragmented primary evidence and creating a model in order to support a rigorous analysis of a building that is lost, damaged or unbuilt. The reconstruction of the lost model of Stirling's design is used as a vehicle to explore and describe the techniques, implications, limitations and outcomes of the process. The forensic techniques adopted mean that we can go beyond simple reconstruction and interrogate the design decisions through a systematic computer mediated process.

3. Precedents and parallels

Beyond the use of modelling to produce reports of existing buildings or predicted appearances and functions of buildings that may be built, digital techniques can also be used to investigate the past in the form of reconstructions. From this, propositions can be made, and these are referred to as *counterfactuals* (Ferguson 1997; Mitchell 1998). A *reconstruction* is a model of a design that has been lost, destroyed or never built. The primary information is almost always incomplete meaning that investigation is needed as of how to fill in the missing parts. A counterfactual involves the development of an argument from this construction, usually a 'what if?' scenario. Questions can be raised such as 'how would this design scheme have influenced the design of subsequent buildings near the site?' Such enquiries can take advantage of what can be called *digital forensics*; a process which aims to provide rigorous investigation in the construction of a model (Harfmann and Akins 2000).

Once the models have been built they can then form the basis of analysis through *scenario building* by developing these 'what if?' questions to suggest an alternative truth which forms 'the start of a trajectory along a postulated historical path and associated circumstances' (Brown 2001). The process of scenario building aims to enhance and augment understanding of a piece of architecture, or an architect's work. The authors creating the scenario are aiming to generate instructive new material. When these concepts are used, they have the ability to form the basis of a much more critical investigation into a design than reviewing two dimensional sources alone. Therefore, by employing these techniques, the advantages from a research perspective are considerable.

4. Case study: Piecing together the Stirling information

One major difference between the studies discussed above, and the Stirling Newton Aycliffe Community Centre model was that the artefact to be recreated primarily took the form of a physical scale model. This enables a unique take on investigating digital forensics and reconstruction that uses both manual and digital techniques.

Various primary and secondary sources were studied to gather enough information to construct the model of Stirling's design. The first of these was to investigate the history of the Liverpool School of Architecture in the period leading up to his thesis project in 1950; when the school was undergoing a period of transition. In the years before the Second World War it had been associated with traditional styles such as the Beaux Arts and Neo Classicism under Sir Charles Reilly. The arrival of the Modern Movement in mainland

Europe began to filter through to the students in the 1930s which was assisted by the arrival of the Polish School of Architecture who took sanctuary in Liverpool in 1942-43 (Rowe 1984).

The writings of Rowe, Stirling's tutor, also formed key sources in understanding the community centre thesis. Rowe commented on the precedent studies Stirling used for the design including the unbuilt Illinois Institute of Technology Library and Administration building by Mies van der Rohe as well as the St Dié factory in France by Le Corbusier (Jacobus 1975). With this knowledge an investigation into those designs was carried out to look for similarities as to what Stirling's intentions could have been in the missing elements of the design. Corbusier's St Dié factory bears a strong resemblance to Stirling's thesis design; the core defining element being a concrete grid structure on pilotis. The fenestration is also likely to have been an inspiration to Stirling; prefabricated timber frames that are mirrored and paired to create a facade that links to the modular nature of the grid, yet retaining variety relating to the various functions of the building (Gans 2006). The scheme provides vital clues of materiality and space as to how the community centre design may have looked if it had been built. Mies van der Rohe's unbuilt library scheme at IIT also forms a good source of extrapolation for the model offering insights into the possible materiality of the design, such as the use of brickwork between the floor level and window sill.

5. Interpolation based on the contemporary context of the model

Inspection of the original drawings for constructing the model revealed that the missing information included the second floor plan, roof plan, both short elevations as well as several courtyard elevations. The problem of the short elevations was in part solved by manipulating a perspective image that included one of these elevations (see figure 1).

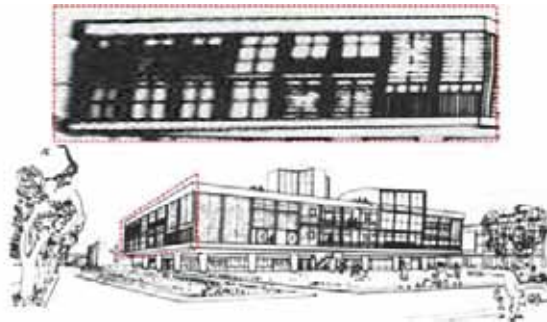


Figure 1. Stirling perspective (above) was digitally orthorectified to gain a clearer indication of the facade pattern (below).

This formed a reasonably clear indication of Stirling's original intentions in relation to the short elevation. The remaining short elevation proved a more difficult issue to resolve; an original section drawn through that part of the design revealed that the internal floor levels changed from being equidistant to a lower floor to ceiling height on the first floor, consequently making the second floor higher. At this point a detailed study of the existing drawings was required in order to work out where this change in level appeared on the external elevation. This change was already visible on the rear elevation of the scheme, of which drawings were available, and ended somewhere along the missing short elevation. As the design was based on a formal grid, it was feasible to interpolate based on examining the rear elevation and section. By studying these it became clear that the change in level took place in the library. Therefore by looking at the first floor plan, and locating the library, it was possible to determine to a relative degree of certainty whereabouts the change in grid pattern ended along the missing elevation (see figure 2). Without this line of enquiry to follow, it is unlikely that someone inspecting the drawings would realise that a change of level occurred in the design.

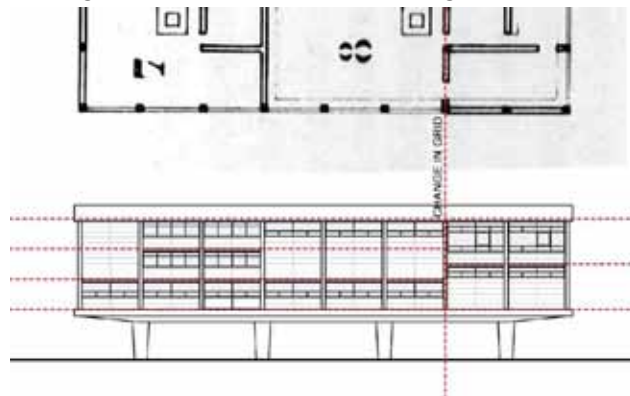


Figure 2. The interpolated short section: the change in grid pattern was discovered by studying the original plan to see where the library was situated.

The centre of the design features two courtyards which are separated by a promenade deck and games deck (see figure 3). The process of constructing the model revealed an inconsistency with the internal columns supporting this element that is not apparent from looking at the existing drawings alone. Two versions of the ground floor plan were available for Stirling's design; the first being less detailed than the second that suggests it was an earlier version. The first plan shows the columns positioned centrally in the internal courtyard which were of the same design as the majority of the columns (circular in section with their diameter increasing as they rise). The second, later plan

employs a different column design altogether; rounded extruded rectangles. When this information was applied to the digital model used to create the physical model, the structural grid informed the position of the columns based on their location on the ground floor plan as described above. Once they were drawn in three dimensions it became apparent that their positioning meant they would protrude past the facade they were supporting above, which is almost certainly an error on Stirling's part. This is especially true as the earlier plan with centrally placed columns suggests the change in column design was last minute.

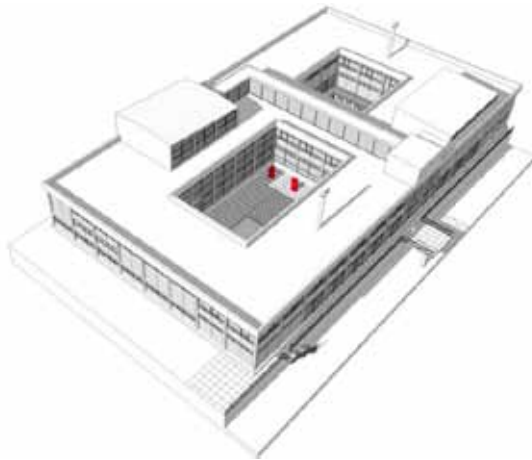


Figure 3. Digital model of Stirling's design showing the repositioned columns highlighted.

After the model was completed, further study of the original drawings revealed that the columns shift away from the structural grid slightly on the section but remained in line with the grid in plan (see figure 5). This indicates that the section was drawn after the plan once Stirling had realised the problem. One can imagine with the deadline approaching, the thought of moving the columns in plan by a barely noticeable amount would have been low on Stirling's list of priorities. However, this inconsistency meant that a decision had to be made as to where the columns should be positioned in the reconstructed model, bearing in mind that at this point their amendment in section was not realised. It was decided to keep the columns in line with the structural grid and rotate them by ninety degrees (see figure 4). This seemed like the most appropriate course of action seeing as the rigorous structural grid underpinned the whole scheme. This highlights a problem with constructing models based on partial information in that it is almost impossible to gain certainty of their accuracy. The practice has been regarded as 'slippery' as the distinction between what is fact and what is supposition or interpolated can be blurred (Mitchell 1998).

This issue can be addressed in the way the reconstructed model is presented; for instance elements of the design that are unknown or based on educated guesses could, for example, be presented in a different manner, by being left empty or shown with less detail than the known elements (Kensek 2005).

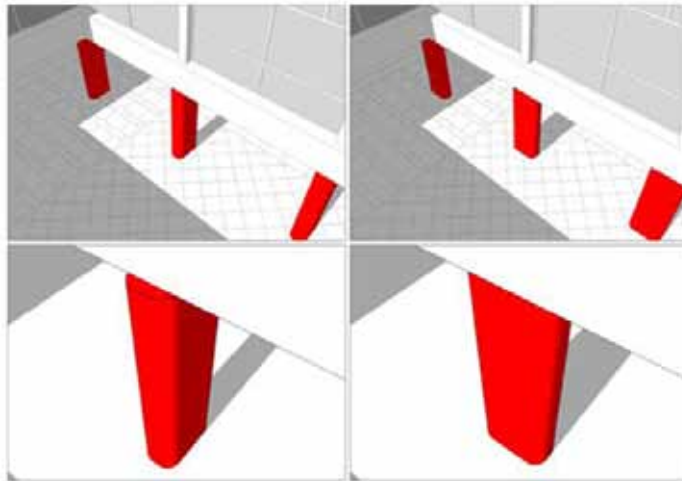


Figure 4. Digital model showing Stirling's final design with overhanging columns (left) and amended design (right).

One puzzling aspect of the design was the space Stirling created between the ground and first floor. At first glance of the drawings, it appeared that the vertical elements of the ground floor area meet the underside of the first floor slab (see figure 5). Upon closer inspection when preparing the drawings for the model, it became apparent that they do not meet; Stirling only connects the two levels where the circulation punches through the first floor slab. This is an example of how drawings alone can be deceptive; the construction of a model allows a more thorough analysis of the design in question and shows the advantages of it as a tool for augmenting architectural research.

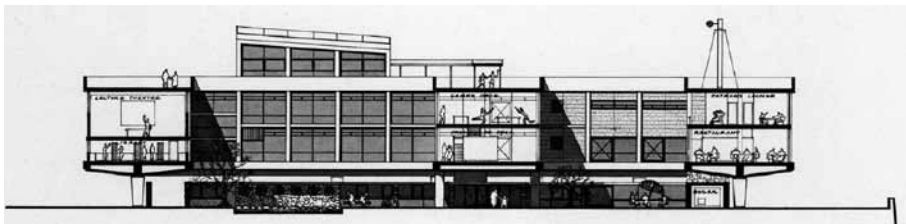


Figure 5. The original section showing the gap between ground and first floors as well as the columns below the deck appearing to sit correctly.

6. Constructing the Newton Aycliffe Community Centre model

Once all of the information was pieced together, the process of constructing the model could begin. Firstly all of the existing drawings were scanned onto a computer and scaled to size using a digital drafting package. The original drawings included a scale bar meaning that this was a simple process in ascertaining accurate dimensions. These sizes were checked by measuring people and door heights for clarity. The size of the grid pattern was established next, as it underpins the whole design. This was calculated at 9700mm (32 feet) between supporting columns and subsequently 4850mm (16 feet) between each window module on the facade. After these ruling factors were recognised, the rest of the drawings were traced over digitally as two dimensional vectors using the grid system as a guide. Once the existing known elements of the design were converted into digital line drawings, the process of filling in the missing elements could begin. This interpolation and extrapolation was carried out based on the research described previously.

After the vector based drawings were completed, they were reconfigured to prepare them for physical production on a CNC router. The process involved converting the drawings into the various layers that form the model. For instance, transparent acrylic was used for the glazed elements; therefore all of the drawings containing glazing were converted to this layer. In terms of representation, it was decided to allow the materiality of the design to be interpreted by the viewer as Stirling had not specified what each material was supposed to be (Knight et. al 2001; Kensek 2005).



Figure 6. Reconstruction of the lost physical model of Stirling's design for a community centre at Newton Aycliffe.

The construction of the model involved the use of both manual and digital techniques. Either alone would not have been enough to provide a satisfac-

tory result. The router cut the numerous pieces based on the digital line drawings and were finished manually by sanding and gluing them together. Some aspects of the design were highly sculptural, such as the weather vanes on the roof, and were consequently produced entirely by hand.

There were several lessons learned in constructing the model which could help with future exploration into digital modelling as a tool for augmenting our understanding. In terms of the missing elements of the design, primarily the missing elevation, a different approach could have been taken to ensure the viewer of the model does not believe it is an exact replica of Stirling's original design. Firstly, the elevation could have been left blank or to only show the grid pattern which runs through the whole scheme ensuring the viewer realises that this element of the design is unknown; however, this would have left the model disjointed and because of the research undertaken it was felt that an extrapolated design was sufficient. Another way of resolving this would have been to present several options of how the facade could have looked (Novitski 1998). This would have been an unhelpful complication when you consider that the model was intended for public viewing in the exhibition and was shown as one piece within the display to illustrate Stirling's Newton Aycliffe Community Centre design from Liverpool University rather than an investigation into what the missing elevation may have looked like. This issue could have been highlighted more clearly within the display though; with information showing which parts were unknown and which involved extrapolation from the known elements. This could also have included a brief description of the process of extrapolation to make the viewer fully aware of the nature of the model.

7. Conclusions and reflections

The production of digital or physical scale models to reinterpret lost or unbuilt designs is highly valuable as a research tool. It enabled a rigorous and thorough analysis of Stirling's Newton Aycliffe Community Centre design, resulting in new information being found. The process revealed that three dimensional modelling is particularly good at aiding the interpretation of a design, rather than relying on a set of two dimensional viewpoints. It also enabled the known and unknown elements to be easily distinguished from each other using the layer structure.

Virtual reconstruction allows an advanced level of understanding of lost architecture, giving an insight into a world that once was. This is valuable in gaining knowledge of our history and heritage in a way that engages the viewer on a much greater level than the study of two dimensional images and text alone. This can be said for reconstructions of models as well as three

dimensional modelling in general, either digital or physical. The World in One School exhibition is testimony to this as the Newton Aycliffe Community Centre model was commissioned for that reason; it enabled the attendees to experience and understand the design far better spatially. Without the use of digitally augmented techniques the model would have been incomplete, giving the viewer a disjointed vision of the design. Therefore its application was necessary and resulted in twofold benefits; a complete design for the viewer and a more thorough investigation into the building by the researcher.

The study demonstrates how thorough the exploration of a design has to be in order to produce satisfactory results, which consequently leads to a highly engaging research experience and augments the investigation into works of architecture. The resulting model, in the case of Stirling's design, creates a lively debate of what was and what could have been.

Acknowledgement

The authors would like to thank Stuart Carroll for his contribution in constructing the Newton Aycliffe Community Centre physical model.

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TOWARDS MORPHOGENETIC ASSEMBLIES

Evolving performance within component-based structures

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Abstract. Performative design can be understood as the combined usage of spatial analysis simulations and form generation procedures to imbue architectural form with material characteristics and behaviours which define desirable structural, environmental and economic performance. However, to date, design processes that facilitate the integration of ‘form generation’ and ‘spatial analysis’ remain under-developed, making existing performative design methodologies highly reliant upon the manual execution of analysis and evaluation procedures. This paper presents an evolutionary design process that uses integrative computational pipelines and generatively defined component-based assemblies to produce performative structures in response to solar performance. The resulting structures demonstrate how performative composite behaviour can emerge within ‘disassociated’ componential assemblies and produce complex formal interrelationships which surpass simplistic parametric logics. This offers new possibilities for conceiving highly integrated ‘morphogenetic assemblies’ and suggests trajectories for further research within the field of morphogenetic design.

Keywords. Morphogenetic; evolution; performative, assemblies.

1. Introduction

Performative design can be understood as the combined usage of spatial analysis simulations and form generation procedures to imbue architectural form with material characteristics and behaviours which define desirable structural, environmental and economic performance. However, to date, design processes that facilitate the integration of ‘form generation’ and ‘spatial analysis’ remain under-developed, making existing performative design methodologies

highly reliant upon the manual execution of analysis and evaluation procedures. This disconnection between 'form generation' and 'spatial analysis' has been widely discussed (Kolarevic, 2003; Kolarevic and Malkawi, 2005; Oxman, 2008; Fernando et al, 2010; Toth et al, 2010) and has prompted new research with a focus on highly integrated early stage design processes using 'computational morphogenesis'.

Morphogenesis is the biological process of growth and differentiation which occurs to form the structure of an organism. Within architecture the term 'computational morphogenesis' is used more generally to describe bottom-up form-finding processes that manage form and performance simultaneously, thereby facilitating the emergence of performative architectural characteristics. Whilst much work has been done to define a theoretical framework within which to situate 'morphogenetic design' methodologies (Hensel et al, 2006; Roudavski, 2009; Oxman, 2009; Leach, 2009), successful implementation of such methodologies are still in the early stages of development (Menges, 2007; Hensel et al, 2010).

Central to the emerging discourse on 'applied morphogenetic design systems' is an understanding of architectural form existing as 'complex assemblies' which operate with non-linear behaviour and are comprised of highly integrated and heterogeneous sub-components, in a manner analogous to the structure of rudimentary natural ecologies.

The operation of natural ecologies has since become an important mechanism for understanding 'morphogenetic design systems' for two principle reasons. Firstly, as Wiscombe (2010) discusses, natural ecologies are able to express 'extreme integration' between their constituent elements making them highly efficient and adaptive systems; that, in contrast to traditional architectural design, are not defined through a layering of engineered parts but instead, emerge out of a massively parallel and 'messy' accumulation of local interrelationships and dependencies. Weinstock (2006) suggests that such integration and complexity requires systems that produce redundancy and differentiation which conflicts with traditional engineering concepts of optimisation and standardisation. Secondly, the self-organising properties of natural ecologies provide rich potential for early stage design systems. Menges (2007) suggests that design approaches that embed analytical procedures into the early stages of design are capable of producing far greater integration of performative qualities than methods which rely upon post rationalisation and mass production.

This paper presents an evolutionary design process that uses integrative computational pipelines and 'generatively' defined component-based assemblies to produce performative structures in response to solar radiation, daylighting and economic material usage.

Throughout this paper the term '*assemblies*' will be used to refer to component-based systems which operate with bottom-up control(s), whereas the term '*formal strategies*' will be used to discuss emergent form-based character traits derived from morphogenetic design processes.

2. Evolutionary computation

Evolutionary computation is often used within existing morphogenetic design systems as a means of finding formal and behavioural properties which perform efficiently in response to explicitly defined design criteria.

Evolutionary computation can be defined as a process of solving non-linear problems using populations of candidate solutions that breed or die according to how well they fulfil a given criteria and can be considered roughly analogous to Darwin's model of natural selection. Various types of evolutionary algorithms have been applied to design, see Bentley and Corne (2001) for an extensive overview; however, within architecture there have been two primary uses of evolutionary computation. Janssen (2006) introduces two terms for these types of application: 'Parametric evolutionary design' which is used to optimise a set of parameters that define an architectural solution in the late stages of design and 'generative evolutionary design', initially pioneered by Frazer (1995), as a means of explorative 'form-finding' in the early stages of design.

There are several examples of 'parametric evolutionary design' which use genetic algorithms (GAs) to evolve architectural form in response to environmental feedback, including Cladas (2008), Kawakita (2008) Besserud and Cotton (2008) and Turrin et al (2010). All of these authors successfully demonstrate the use of an iterative design process that integrates 'environmental analysis' and 'geometric transformations' to produce performative structures. However, they all rely upon extensive parameterisation, which render them incompatible with morphogenetic design strategies for two reasons. Firstly, as the models require definitive parameterisation prior to evolutionary processes, the application of the GA is limited to late stage design and parameter optimisation. Secondly, simplified parametric encodings tend to favour isolated optimisation of particular components rather providing the potential to construct new interrelationships between components and define composite behaviour. As Cladas (2008) states, future developments of existing studies require "a method of incorporating functional and spatial requirements while allowing for the emergence of shapes that we not initially specifically encoded" within the parameterised model (Cladas, 2008, p.69).

Within computer science much research exists which illustrates the creative potential of evolutionary computation beyond parameter optimisation

(Bentley, 2000; Bentley et al, 2001; Hornby and Pollack, 2001; O.Stanley and Miikkulainen, 2003). These studies suggest that when evolutionary systems use parameters which do not directly represent the design solution, thus tending towards 'generative evolutionary design', it is possible to construct efficient design solutions which are not restricted by the initial parameters. Similarly within architectural discourse the possibility of producing performative structures which surpass limited parametric-based design representations has been discussed by Janssen et al (2002), Frazer et al (2002), Janssen (2006), Menges (2007) and Ahlquist and Fleischmann (2008). These authors have demonstrated how indirect design representations can be managed within an evolutionary computational framework to output highly diverse, yet performative, formal characteristics.

The objective of this paper is to demonstrate how we might extend existing 'parametric evolutionary systems' towards 'morphogenetic design systems' that integrate generative and analytical procedures and surpass optimisation, suggesting novel 'formal strategies' which exist beyond a narrow spectrum of possible formations. This is approached by firstly, addressing how parametric 'assemblies' are encoded and processed as part of an evolutionary design system; and secondly, by establishing an alternative design methodology that advocates scripting and 'novel computation' within open-source programming languages to facilitate communication, or 'integrative pipelines', between existing CAD and analysis platforms.

3. Project description

This project builds upon existing studies (Cladas, 2006; Kawakita, 2008; Besserud and Cotton, 2008; Turrin et al, 2010) and provides an alternative approach to evolving efficient material assemblies in response to solar performance. The project develops a series of small scale 'pavilion' structures, each of which are 4m x 4m x 2.5m free standing structures that seek to minimise direct solar radiation to an internal space, whilst minimising material usage and maximising natural daylighting. The pavilion structures are created by populating a surface with a collection of components that define static assemblies and express passive solar performance.

The core computational framework has been developed within the open source scripting environment 'Python' and consists of a GA and scripted pipelines to the CAD packages '3ds Max' and 'Ecotect' in order to perform 'form generation' and 'solar analysis' processes remotely. The following section precludes a detailed technical description of the computational workflow, which will be discussed in a separate paper, but instead focuses on how three principle aspects of the evolutionary system, component encoding, integrated analy-

sis and selection, contribute towards a morphogenetic design strategy.

3.1. COMPONENT ENCODING

In order to discuss an extension of ‘parametric evolutionary systems’ towards ‘morphogenetic design systems’ it is important to first address how ‘parametrically’ encoded structures can be converted into ‘generatively’ encoded structures and how this difference is qualified. Rather than viewing parametric and generative encoded models in binary opposition we may, as Bentley (2000) discusses, consider the difference characterised by how knowledge-rich or knowledge-lean the design representations appear. ‘Knowledge-rich’ representations are more rigorously defined and parameterised, such that changes made to parameters have predictable effects within a limited spectrum of formal possibilities. In contrast, ‘knowledge-lean’ representations are constructed from a collection of lower level components which are less constrained to limited transformations, thus design representations have much more varied and less predictable formal possibilities.

In this project each pavilion structure is composed from a collection of components which populate a host surface. Figure 1 illustrates the method by which each component is encoded and compares this with a commonly used knowledge-rich component used within previous ‘parametric evolutionary design’ studies.

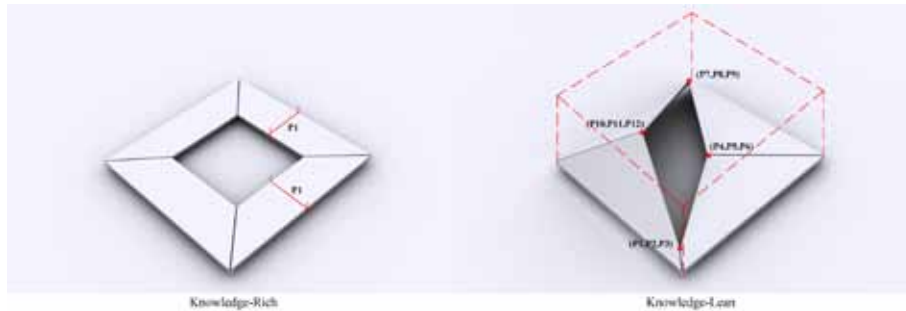


Figure 1. Component encoding mechanism

Each component is defined by the location of four vertices which are permitted to be positioned freely within a volume that is defined relative to the populated surface normal. The vertices are then combined to form a three dimensional component which has many formal possibilities and is therefore considered ‘more’ knowledge-lean when compared with conventional knowledge-rich parametrically encoded components. The encoded instructions, which define

the complete positions of all component vertices of any pavilion structure, are stored as a string of digits on a text file and become the pavilions' genetic description (or genome).

3.2. INTEGRATIVE ANALYSIS

'Python' is used to construct a unifying computational framework between existing CAD and analysis software to enable integration between generative and analytical procedures.

Once pavilion structures have been generated from their genetic description they are exported to 'Ecotect' for environmental analysis. Here two calculations are performed. The surface beneath the pavilion is split into 156 segments and each segment is assessed for how closely it meets a specific daily 'solar radiation' value and 'daylighting factor' value. The result of these calculations is two numbers which represent the accumulative differential between an ideal (uniform) solar radiation value and an ideal daylighting factor value - the optimum solar radiation being a low value and the optimum daylighting factor being a high value. These two values are then combined with a measurement of how much material is used to construct the pavilion to produce a singular fitness score; the fittest pavilion being that with the lowest score (smallest differential between solar radiation and daylighting values and least material used).

This information is then stored within 'Python' so that each genetic description can be compared to a population of similar structures for how well it 'performs' to minimise direct solar radiation and material usage whilst maximising natural daylighting.

3.3. SELECTION

Each generation of pavilions comprises of a population of 100 candidate structures which have been generated from genetic descriptions and analysed for solar performance. The next step in the evolutionary design system is to select structures which will reproduce to create new genetic descriptions for the next generation and thereby complete an iteration of the design process.

The GA uses 'tournament selection' to maintain formal diversity within the population of structures whilst selecting structures to breed to create new genotypes for the next generation. In this process 5 structures are selected at random from the possible 100 and ranked; the fittest two are then combined using a crossover function and subjected to potential mutations to produce a new pavilion genotype. Rather than seeking to always breed the best structures together which can quickly homogenise the population of possible solu-

tions, tournament selection slowly eliminates the worst performing structures and is more forgiving to initially detrimental or redundant character traits. This provides the potential for novel component interrelationships to emerge over time, thus transforming initially inefficient formal quirks into actively performative formal qualities that are not explicitly encoded by the component parameters.

4. Results

This section compares two pavilion structures that are each the result of 150 generations of the evolutionary development. The first structure is defined by the knowledge-lean components described in the previous section. The second structure is defined using conventional knowledge-rich components (as illustrated in figure 1) which correspond to ‘parametric evolutionary design’ design representations that have proven successful in generating highly efficient formal organisation in previous studies.

Figure 2 illustrates the passive solar performance of the two pavilion structures and demonstrates how the two structures have evolved in relation to four performative aspects: average fitness, average daylighting, average solar radiation penetration and average material usage.

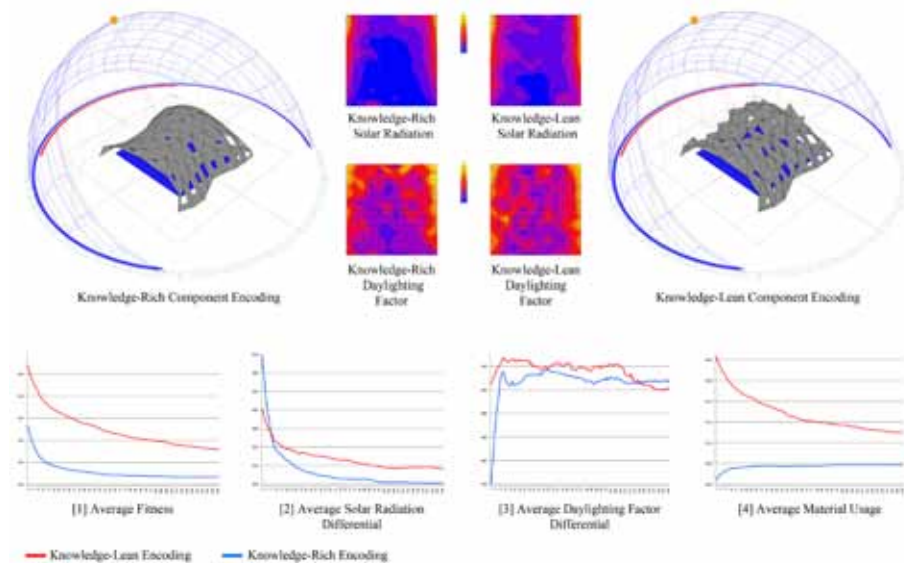


Figure 2. Top- Comparative pavilion performance. Bottom - left to right: average fitness, average solar radiation, average daylighting and average material usage

The graphs in figure 2 demonstrate that the knowledge-rich structures are able to define more efficient structures much more quickly than the structures with knowledge-lean encodings. This is primarily due to the relative length of the genomes, the knowledge-lean structures being 12 times longer, this significantly increases the space of possible solutions making it much harder to find optimal results through evolutionary search. However, the largest contributing factor to the comparative fitness of these structures is the large difference between material usages – the three-dimensional knowledge-lean components using considerably more material than the knowledge-rich components which are limited to a two-dimensional plane.

These results support existing studies and demonstrate that knowledge-rich encoding systems coupled with evolutionary design processes can produce successful optimization systems. However, the strength of knowledge-lean encodings and vast potential for morphogenetic design is evidenced by comparing the behavioural properties of each structure.

Figure 3 illustrates how solar rays behave upon hitting the surface of each structure and the subsequent ‘formal strategies’ that emerge. The knowledge-rich components behave in a predefined manner oblivious to the reflected rays. In contrast, the knowledge-lean components are able to exploit the daylighting potential of the reflected solar rays by adapting their geometries in such a way that they actively bounce light off neighbouring components and into the interior space. Therefore the knowledge-lean encoding produce highly complex and integrated composite behaviour that is not predefined but emerges through time in a manner analogous to ecological structures.

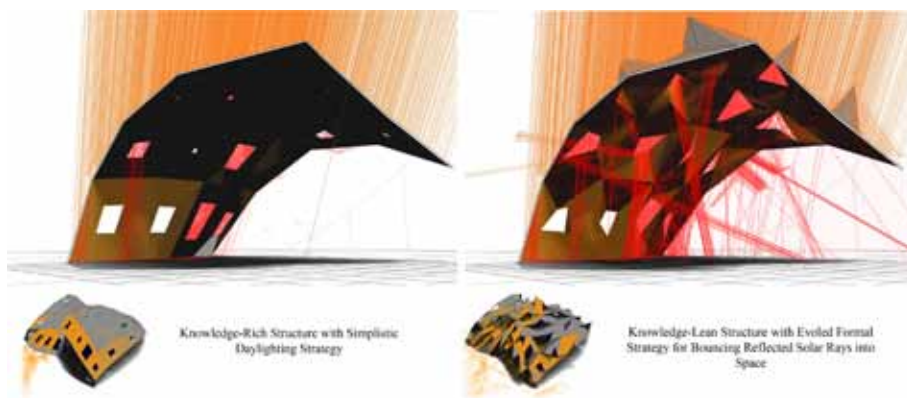


Figure 3. Emergent formal strategies

7. Conclusions

This paper demonstrates how architectural assemblies defined by knowledge-lean encodings and processed via a genetic algorithm, can acquire performative formal attributes in response to environmental stimuli.

Currently this system does not consider the material properties of emergent structures or related construction processes, which are required to develop material-specific ‘formal strategies’ and define highly integrated ‘morphogenetic assemblies’. However the methodology presented does allow for expansion and the inclusion of additional analysis procedures via integrative scripted pipelines. Simulation run-times within the evolutionary design system currently present a severe limitation; however, recent research has evidenced how such design processes might be distributed over multiple computers to significantly reduce run-times and increase the creative potential for future applications in early stage design (Janssen, 2009; Turrin et al, 2010).

Further research is now underway and seeks to explore how material and structural properties can be embedded within knowledge-lean assemblies to facilitate the production of highly integrated ‘morphogenetic assemblies’ that express material-specific formal attributes and performative composite behaviours.

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CLOSING THE LOOP OF DESIGN AND ANALYSIS

Parametric modelling tools for early decision support

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Abstract. There is a growing need for parametric design software that communicates building performance feedback in early architectural exploration to support decision-making. This paper examines how the circuit of design and analysis process can be closed to provide active and concurrent feedback between architecture and services engineering domains. It presents the structure for an openly customisable design system that couples parametric modelling and energy analysis software to allow designers to assess the performance of early design iterations quickly. Finally, it discusses how user interactions with the system foster information exchanges that facilitate the sharing of design intelligence across disciplines.

Keywords. Parametric; performance; analysis; integration; energy.

1. Introduction

While parametric modelling is becoming an increasingly integral part of many computer-aided design (CAD) tools, its potential to provide dynamic and responsive performance analysis, through integration with building simulation, has long eluded the architectural domain. Pioneers of CAD predicted a design process that exploited the analytical powers of the machine to enhance the creative powers of the designer (Coons, 1963). They portrayed a system based on associative modelling, where designers refine digital concept

sketches iteratively in response to feedback obtained from analyses carried out by the computer (Sutherland, 1963). However, while parametric modelling systems today have succeeded in establishing associative methods for defining and exploring design constraints, few have been developed to incorporate performance feedback into this design process.

Limitations in both tools and process pose challenges to the integration of simulation in early design. The conversion of 3D models between design and analysis representations is not well supported by existing data transformation mappings, and typically requires expert translation and interpretation (Augenbroe et al, 2004). Furthermore, most simulation tools necessitate detailed information about a building's construction and services before even an indicative analysis can be performed; information that may not be available at the conceptual design stage (Ellis and Mathews, 2001). These incompatibilities inhibit the development of an interactive information exchange network where design and analysis processes are active simultaneously, and serve rather to reinforce conventional practice where one domain is active and the other reactive (Nicholas and Burry, 2007). What is needed instead is a dynamic and concurrent performance evaluation process that parallels the characteristics and logical relationships of the design process, and permits smooth transitions between domain-specific representations.

While strategies for integration are often seen to revolve around software interoperability, design communication networks also play a critical (yet sometimes forgotten) role in establishing clear relationships between design and performance constraints. This paper therefore examines not only *how* data is exchanged, but also *when* and *what* information is shared between disciplines. It focuses on the interaction between architectural design and energy analysis to demonstrate how integration can be achieved in domains where geometry is not necessarily a common foundation.

2. Open versus closed circuits

The industry's preoccupation with software interoperability over the last two decades (Boddy et al, 2007) has led to the development of 'open circuit' practices that do not support responsive feedback between domains. As a result, designers rely predominantly on intuition and rule-of-thumb to make decisions, despite these techniques lacking the capacity to quantify the performance impacts of design decisions against the complexity of project constraints (Bambardekar and Poerschke, 2009). Subsequently, rather than playing a role of decision support in the design, analysis is used primarily to verify and rationalise decisions already made (Hopfe and Hensen, 2009).

These open circuit processes can be seen in Figures 1 and 2, which illus-

trate the two most commonly adopted methods for exchanging information between domains. Both are based on a strategy of *data model interoperability* and rely on programs sharing information at the level of the product model (Citherlet et al, 2001). Model exchange achieves this via a neutral file exchange format that serves as a generic common representation, while model sharing involves a single data management system that contains the entire building description from which domain-specific applications can extract required information (Citherlet et al, 2001). In both cases, design and analysis models are developed separately, which often results in data redundancies and inconsistencies between representations (Schlueter and Thesseling, 2009). Additionally, neither scenario can support the rapid and interactive transformations required to generate responsive performance feedback.

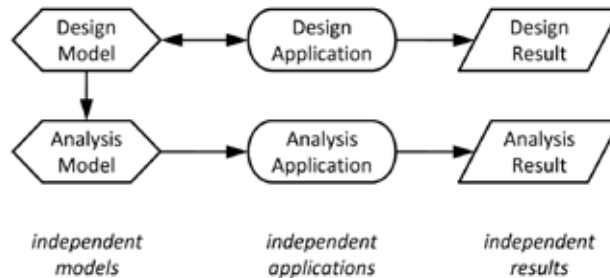


Figure 1. Data model interoperation: model exchange.

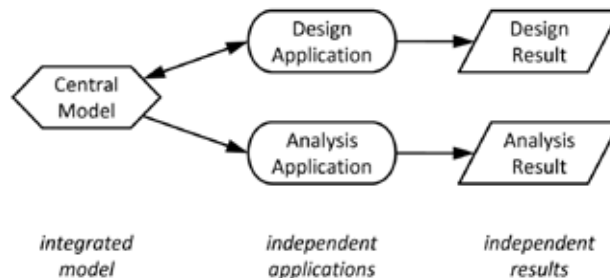


Figure 2. Data model interoperation: model sharing.

What is needed instead is a closed circuit approach that allows information to be dynamically exchanged in a feedback loop throughout design exploration (Janssen et al, 2002). A *data and process model cooperation* approach is currently emerging as an alternative strategy for information exchange that enables this feedback. In this scenario, programs are effectively coupled by providing the facility to link to other applications at run time (Hensen, 2004). As illustrated in Figure 3, one program controls the evaluation process and

invokes other applications as required, automatically generating necessary analysis models and performing simulations (Hensen, 2004). As a result, information is able to be cooperatively exchanged during the design process in a manner that is readily customisable. This research finds the cooperative approach to be vital to the development of performance-oriented design tools for early design.

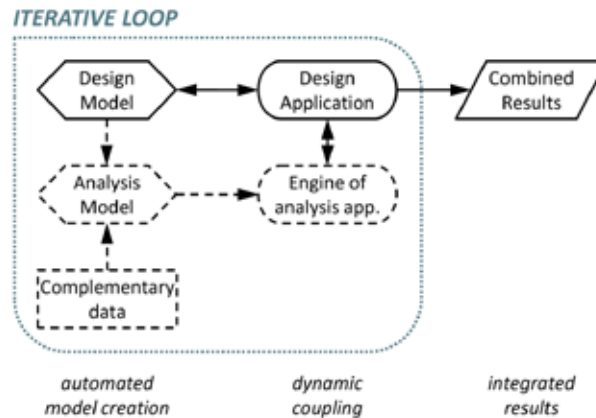


Figure 3. Data and process model cooperation.

3. Energy-oriented design in practice

Despite the proliferation of energy simulation tools in the last decade, few connect to the actual analysis needs of the designer. The majority that attempt integration, such as IES Virtual Environment and Trace 700, typically implement model exchange or model sharing strategies to achieve information transfer with BIM (Building Information Modelling) software, in a manner that is not customisable, and are more suited to the late stages of the design process. Those applications that do target early design often engage a program coupling approach, usually in combination with ‘push/pull’ modelling techniques, however, pose their own obstructions to integration. Many, such as Autodesk’s Project Vasari, employ simplified simulation tools that engineers regard as too unreliable for use in systems design, and subsequently inhibit collaboration between disciplines. Others, like the OpenStudio plug-in for Google’s SketchUp, use validated simulation tools, but are incomplete in a collaboration sense as the coupling link deals only with the translation of geometry between programs, and not material properties, building systems, or occupation. Additionally, none of these tools implement parametric modelling capabilities to explore design constraints.

Recent research from Stanford has demonstrated that when a program coupling methodology is combined with parametric geometry definition, a greater number of design iterations and improved performance outcomes result (Flager et al, 2009). Further building on this research is Arup's DesignLink (Arup, 2010). This domain-independent platform uses customised plug-ins to couple parametric modelling and performance analysis applications, subsequently generating trade-off evaluations of constraints (Holzer and Downing, 2010). At present however, there is a predominantly structural flavour to the analysis software that has been linked to the platform, and a focus on the translation of geometry between domains. This research therefore seeks to build on this existing knowledge by examining how representational frameworks can extend beyond a geometric understanding of a building to include the association of behavioural attributes.

4. Parameters and representation

To ensure a common understanding across domains, a unified conceptual framework that identifies and redefines key performance parameters as design-related criteria must be established. From recent investigations into energy analysis undertaken by the primary author, seven groups of parameters have been identified as necessary in constructing an early energy model (Toth et al, 2010). These are as follows:

1. Thermal Zones (used as the geometric construct rather than rooms);
2. Glazing and Skylights;
3. External Shading;
4. Construction Types;
5. Internal Gains for Occupancy, Equipment and Lighting;
6. HVAC Systems; and
7. Weather and Environment.

Rather than following the existing trend of high resolution BIM data structures, a simplified representation schema that connects these seven parameters must be developed to achieve a greater degree of integration with the analytical domain and a level of detail suitable to early design. Energy simulation requires building geometry to be expressed as a series of zones defined by closed sets of planar surfaces, to which performance attributes are attached (Dong et al, 2007). This surface-based representation is considered suitable for conceptual design when architectural considerations are limited to basic form and spatial organisation. Since parametric design environments do not recognise the constructs of 'zone' and 'surface', new representations must be created to ensure semantic compatibility. Each 'surface' is based on the

geometry of a polygon, with the addition of a ‘construction type’ property to allocate conductance values. A ‘zone’ adopts a solid geometry to represent its volume, and requires the properties of ‘activity’ and ‘HVAC system’ to determine internal gains and equipment loads respectively.

To avoid overcomplicating input requirements, the designer must be able to simply tag the geometry within the model to indicate the required attributes, and have these tags translated to the relevant numerical values when the analysis procedure is invoked. The system must therefore be able to populate the simulation model automatically with detailed building schedules, thermal conductivity properties, and systems profiles. This requires the development of detailed support databases containing values derived from guidelines and regulations that are well accepted within industry (Morbiter et al, 2001). These databases enable a system to be developed that allows design representations to be transformed into analytical models and evaluated through simulation, without the need for expert interpretation and translation.

5. Proposed design system

This research proposes an energy-oriented design system that couples GenerativeComponents (GC) and EnergyPlus (EP) to create a decision support tool for early design. The structure for this system (which is currently under development) is illustrated in Figure 4.

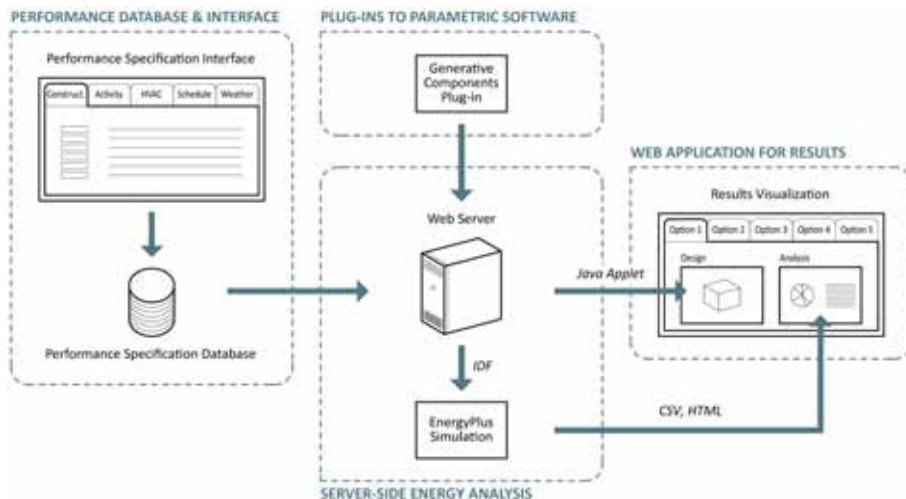


Figure 4. Proposed energy-oriented design system.

This system does not seek to provide exact estimations of operational energy consumption, but rather to offer a reliable means of comparing early design options. By ensuring that a high level of consistency is maintained in the structuring of the analytical models, designers will be able to directly observe the impacts of their decisions by comparing the performance of different design alternatives. The openly customisable design environment establishes a dynamic and cooperative performance evaluation process by linking the modelling application to the analysis procedure through a server-based specification database. Evaluation occurs in close to real time, with results being pushed to a web application that displays design options and performance outcomes side-by-side. The system consists of four key components, which are discussed in the following subsections.

5.1. CUSTOM PLUG-IN FOR PARAMETRIC SOFTWARE

Additional features must be embedded inside GC to ensure that design models contain geometric and behavioural data suitable for energy analysis, as discussed in the previous section. As well as generating simple planar surfaces, these features are designed to accommodate quite complex geometry through approximations using surface faceting techniques. When the energy simulation procedure is invoked from within the modelling software, the plug-in then sends a query to the database to retrieve the relevant attribute data for each property tag, as well as additional information concerning weather and building scheduling. This information, along with the geometric data from the model, is then forwarded to EP to be analysed.

5.2. PERFORMANCE SPECIFICATION DATABASE

A Graphical User Interface (GUI) is used for populating, viewing and editing the performance specification database, which contains the non-geometric data required for energy simulation. This separates the numerical representation of data from the design model, allowing designers to focus on the manipulation of form and space. The database is hosted on a web server, but can also run as stand-alone. Users can work in connected or disconnected modes, depending on the availability of internet connection. In addition to this, the simulation process can also be invoked from within the database, so that building attributes can be further refined once a design is selected.

5.3. SERVER-SIDE ENERGY ANALYSIS

EP performs analysis on a text-based representation of the building data

known as an Input Data File (IDF), which is automatically created when the simulation procedure is invoked. Analysis results are generated as CSV and HTML files, so that they can be displayed directly in the results interface. At the same time, the geometry from the parametric model is stored in the database for on-demand visualisation of the three-dimensional data. This ensures that a snapshot of the design is captured for every simulation performed, to facilitate the tracking of design options and their performance outcomes.

5.4. WEB APPLICATION FOR RESULTS VISUALISATION

As well as displaying the results of the energy analysis, this web application is embedded with a Java applet that displays the stored geometry, so that design options and performance outcomes can be viewed side-by-side. Simplified simulation results are also returned to GC to provide the designer direct access to the performance outcomes within the design environment.

6. Circuits of use

This system aims to create an integrated and interactive design process that facilitates the sharing of design intelligence across disciplines, so that the impacts of design decisions on performance can be clearly understood. It necessitates that common objectives be established upfront so that systems and scheduling appropriate for the spaces of the project can be defined, which creates opportunity for discussion and collaboration between disciplines. Architects and engineers are then able to work concurrently within the system, as illustrated in the use case diagram in Figure 5.

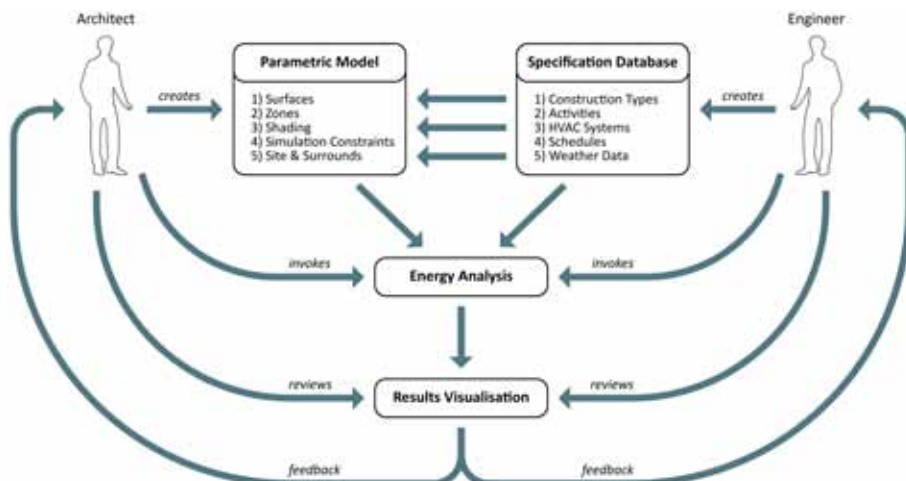


Figure 5. User interaction with the proposed design system.

As can be seen, the different disciplines are able to work in parallel, with the architects undertaking the modelling of different design options, using input from the database that is manipulated and refined by the engineers to ensure accuracy in results. This integrates the typically separate tasks of design and specification to produce a holistic representation of the building, while mimicking the workflows of each discipline. Energy analysis can be invoked from either the modelling or database interfaces, to ensure that both disciplines are able to investigate building alternatives. With the outcomes being published to a common web application, team members are able to review the options simultaneously and make decisions collaboratively.

Typically, one of the primary downfalls of simplified energy analysis applications is that the default simulation data is largely hidden from the user, and often does not reflect the specifics of a project. In response to this, the ability for the user to customise the design environment is a key characteristic of the proposed system. As well as having the freedom to define the non-geometric building attributes through the performance specification database, users are able to extend the actual coupling link as required to include further capabilities such as code-checking. The system is also scalable and accommodates various usage scenarios, from a single user working on a local computer to multiple users accessing the database, server, and results, and can swap between modes of operation at any stage in the design process.

7. Conclusions

While parametric modelling tools have undoubtedly been successful in establishing methods for the rapid generation and flexible exploration of design alternatives, few extend to address performance considerations in early design. This paper presents the framework for a performance-oriented parametric modelling tool that will address this need to facilitate an integrated design process that is *collaborative*, *iterative*, *customisable* and *scalable*. By linking analysis applications to parametric design software, and simultaneously reducing the complexity of simulation inputs to suit early design enquiries, new decision-support tools can be developed that enable designers to assess the performance of design alternatives quickly and iteratively. It is anticipated that the establishment of flexible and concurrent design and analysis environments, such as the one presented in this paper, will open up a dialogue between architects and engineers and strengthen design communication networks. This will support the development of more integrated design practices that facilitate a shared understanding and knowledge between disciplines, which is of as great a benefit to the design process as the performance evaluation capabilities that the system provides.

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TOPOLOGY PATTERN MINING

A visual approach for representing and retrieving design patterns of spatial topology in a case library

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Abstract. This paper aims to apply the clustering analysis algorithm to analyze and classify the pattern of spatial topology of floor plans within a case library named “Open Case Study (OCS)”. Based on the results of classifications, this paper proposes a visual interface named “Topology Pattern Mining (TPM)” to present and rank searching results in response to user’s queries. The purpose of TPM is to extend the capacity of OCS for representing implicit knowledge of spatial topology. TPM can retrieve and classify design patterns of spatial topology, and thereby helps users to learn the design knowledge within relevant cases.

Keywords. Case-based design; case library; knowledge representation; spatial topology; data mining.

1. Introduction

Architectural design cases are important sources for design thinking while cases often lack of visual retrieval mechanism for indexing implicit knowledge. One purpose for developing an architectural design case library is to accumulate the design knowledge and experience obtained from case studies (Kolodner and Leake, 1996). However, the means for abstracting, encoding, and indexing the case information determine the way for how to retrieve, represent, and reuse the knowledge in the design cases.

Currently, an architectural design case library is usually constructed by rational database technology, which requires selecting the most specific common features of a case and then converting those features into metadata of design information. The selected explicit features serve as the indexing

mechanism and knowledge representation of the design cases in the library. However, the indexing mechanism using the explicit features often overlooks the acquisition, re-indexing, and generalization of the implicit knowledge among different cases.

This paper is a follow-up study of a previous project named “Spatial Topology Retrieval (STR).” STR established a visual and interactive tool for encoding and retrieving spatial topology of floor plans within a case library (Lin and Chiu, 2010). The case library is another previous project named “Open Case Study (OCS)”, which is an online house design case library with ontology-based authoring tools of metadata for case’s features (Lin and Chiu, 2009). This paper introduces clustering analysis algorithm to analyze and classify the pattern of spatial topology of floor plans within the case library. Based on the results of classifications, this paper proposes a visual interface named “Topology Pattern Mining (TPM)” to present and rank searching results in response to user’s queries. The purpose of TPM is to extend the capacity of OCS’s knowledge representation, which can not only store spatial topological information, but also retrieve and classify design patterns, which thereby helps users learn the design knowledge within relevant cases.

2. The approach for mining spatial topology pattern

The nature of architectural design is to appropriately create and arrange topological and geometric relations between vacant spaces and physical components of a building. Eastman (1999) proposed the building product models, which categorized a building’s information into three types – geometric, semantic, and topological information – and initiated the researches of building information model (BIM). Nowadays, BIM is already applied in commercial CAAD tools, and is widely adopted by AEC application field. However, most implementations of BIM are more aligned to document generation and final construction application (Howell and Batcheler, 2005). Consequently, those implementations all lack the topological information of the indoor or outdoor spaces, which is required for the early architectural design and performance analysis.

In the early design phase, an architect usually first considers the “topological relationship” among vacant spaces of a building program, rather than detailed geometric properties of physical components. For example, an architect may consider the adjacency among relevant rooms, the circulation formed by the connections of accesses and corridors among rooms, and directions of views formed by the opening, etc. From the view of case-based design, the topological knowledge for how to organize relevant spaces of a building project has been stored in the case itself. However, how to index, retrieve and

represent those design knowledge still remains as a problem for developing a case library. For solving this problem, a case library needs (1) methods for encoding spatial topology of floor plans, (2) algorithm for weighting similarity of spatial topology, (3) algorithm for clustering similar spatial topology, and (4) means for representing the results of classification.

2.1. ENCODING SPATIAL TOPOLOGY

The data model, which represents and reasons topological relationships among spatial features, is an important issue in geographic information system (GIS), but it is usually ignored in CAAD research. Basic topological relationships within GIS include adjacency, overlapping, disjointness, inclusion, etc. (Rigaux, Scholl and Voisard, 2002). However, not all topologies are useful for architectural design, such as overlapping and inclusion. Other relations such as the accessibility, which is formed by accesses between interior spaces, are more important than basic topologies in GIS.

In the previous study, STR therefore modelled three manipulable and two detectable spatial topology for encoding spatial topology. The three manipulable spatial topologies are: (1) adjacency, (2) connection, and (3) combination. The two detectable spatial topologies are (4) opening, and (5) spatial orientation (Figure 1).

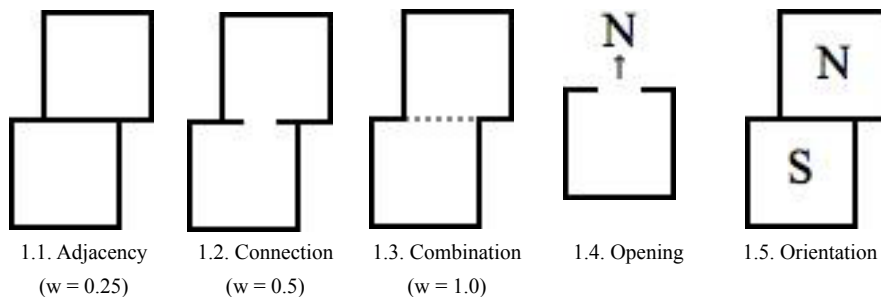


Figure 1. Five spatial topologies in STR.

STR modelled adjacent topology of rectangular spaces as a Boolean type relation, which means that two spaces must be adjacent when assigned an adjacent topology between them, but spaces could be adjacent even without any assigned topology (Figure 1.1). Other two manipulable topologies are extended form adjacent topology. The connective topology, which is built by an access connecting two adjacent spaces, can represent the interior circulation (Figure 1.2). The combining topology, which is built by removing the boundary between two adjacent spaces, can represent a compound space such

as a living room combining with a dinner room (Figure 1.3).

The opening topology, which is built by attaching an opening, can represent the relation of an interior space with outdoor spaces for the view and natural lighting (Fig. 1.4). The orientating topology, which is determined by relative positions of two adjacent spaces, can represent the functional requirements such as a response to the climate or context of the site (Fig. 1.5). However, to avoid complicated inputs in encoding spatial topology, only the first three topologies are manipulatable in STR. The opening topology could only be assigned and detected, and STR automatically detects orientating of opening and adjacent spaces like the early system such as FABEL (Coulon, 1995).

Five topologies may be all useful for present some important knowledge for spatial allocations knowledge in architectural design. However, only first three topologies, i.e. adjacency, connecting and combination, are more important for identifying and weighting relevance of two different indoor spaces, then further to weighting the similarity of spatial allocations among different cases.

2.2. WEIGHTING SIMILARITY OF SPATIAL TOPOLOGY

For weighting the similarity of spatial topology of design cases, TPM assigned different weight to three kinds of topologies, which are: (1) adjacency is 0.25, (2) connecting is 0.5 and (3) combination is 1 (Figure 1.1, 1.2, 1.3). This weighting method can present the relevance of two spaces and keep the scores of similarities among cases less than 1. Every one spatial topology can be regarded as one dimension of a multi-dimensional space. A weighting of the spatial topology can be regarded as a coordinate along the topological dimension. Then distance metrics can be applied to measure the distance between two topological nodes in the multi-dimensional space.

Cosine similarity is a kind of distance metrics applied in data mining, that can measure distance between two vectors by finding the cosine of the angle between them (Tan, Steinbach and Kumar, 2005). For example, there are two cases C_i and C_j , where $i \neq j$, and all cases has n types of spaces in the library. Therefore, the topological weightings of floor plans of case C_i and C_j can be converted into vector T_i and T_j as formula (1). Then cosine similarity algorithm can measure the similarity score of two cases C_i and C_j by formula (2):

$$(1) \quad T_i = [t_{i,1}, t_{i,2}, \dots, t_{i,n}], T_j = [t_{j,1}, t_{j,2}, \dots, t_{j,n}]$$

$$\text{Similarity}(C_i, C_j) = \frac{T_i \bullet T_j}{\|T_i\| \|T_j\|} = \frac{\sum_{k=1}^n t_{i,k} \times t_{j,k}}{\sqrt{\sum_{k=1}^n (t_{i,k})^2} \times \sqrt{\sum_{k=1}^n (t_{j,k})^2}} \quad (2)$$

The higher score of $\text{Similarity}(C_i, C_j)$ means that C_i and C_j are more similar in their spatial topologies. Based on the similarity scores of cases, we can further apply clustering analysis algorithm for classifying patterns of houses' plans in the OCS case library.

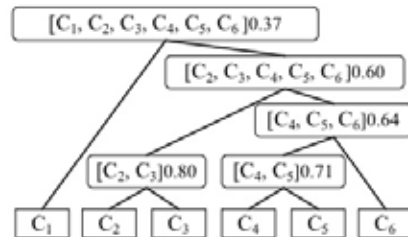
2.3. CLUSTERING SPATIAL TOPOLOGY PATTERNS

Clustering analysis algorithm is a kind of data mining algorithms, such as K-Means for partitional clustering and complete-linkage method (CLM) for hierarchical clustering, which is applied to automatically classify mass data. Since cosine similarity is applied to measure the similarities of spatial topologies of cases in the library, agglomerative hierarchical clustering method should be satisfied and easier for clustering the patterns by ranking the similarity scores among cases.

For example, there are 6 cases in the library and their similarity scores matrix is shown in Figure 2.1. Then, agglomerative hierarchical clustering method can build a binary tree by linking similar cases based on the max score of similarities. Therefore, if no any given threshold, there are 4 levels of 5 different clusters after agglomerated. In other words, there are 5 patterns found in this demonstration (Figure 2.2). Based on the clusters, the system cannot efficiently ranking similar cases of a given cases by user, but also can discover design patterns.

	C_2	C_3	C_4	C_5	C_6
C_1	0.37	0.18	0.37	0.11	0.36
C_2		0.80	0.60	0.37	0.27
C_3			0.55	0.40	0.19
C_4				0.71	0.64
C_5					0.59

2.1. Similarity scores matrix of 6 cases.



2.2. Binary tree by similarity scores.

Figure 2. A demonstration of the agglomerative hierarchical clustering methods.

3. Representation of spatial topology patterns

“Design pattern” is a formal documenting of a solution to a design problem in a particular field of expertise. Therefore, “design pattern” seems to be a satisfied representation of design knowledge within a case library. However, Heylighen and Neuckermans (2001) pointed out that most of early case-based

systems failed to require, re-index, and generalize design knowledge within the case libraries, and not to mention to represent design patterns of cases.

The purpose of TPM is to extend the capacity of OCS's knowledge representation, which can not only store spatial topological information, but also retrieve and classify design patterns of spatial topologies. For representing design patterns of spatial topologies, TPM proposes two approaches for visualizing similarities among floor plans of design cases and individual spaces in separate floor plans.

3.1. HYBRID REPRESENTATION OF FLOOR PLAN PATTERNS

How to display a multi-dimensional vector of data's features on a 2-D screen usually is a problem for visualizing ranking and clustering results in data-mining domain. However, the problem for TPM to display the ranking results of spatial topologies on 2-D screen should be only one metric of similarity scores.

Therefore, TPM takes a hybrid approach, which applies basic geometric features of floor plans, i.e. the differences of total areas of floor plans, as another dimension of similarity. By integrating basic geometric features with topological similarities of separate floor plans, TPM can rank relevant floor plans for retrieved cases, display results of ranking on 2-D screen but avoids confusion. Figure 3 demonstrates the concepts of STM's interface for visualizing retrieved patterns. TPM arranges relevant floor plans along Y axis by topological similarity scores and along X axis by differences of total areas. The distances of Y axis among cases are based the reciprocals of similarity scores. The distances of X axis among cases are based the different percentages of total areas. Therefore, if the retrieved case is C_6 of the demonstrations in Figure 2, then all the 6 cases may be displayed in TPM as Figure 3.

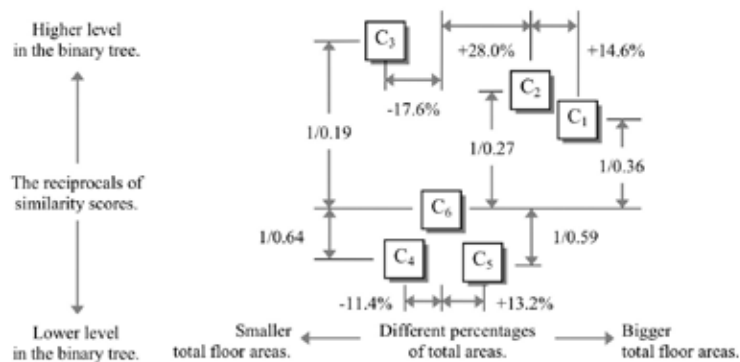


Figure 3. The concept of TPM for visualizing patterns of retrieved cases.

3.2. PARTIAL REPRESENTATION OF SPATIAL TOPOLOGY PATTERNS IN A FLOOR PLAN

The similarity scores of spatial topologies in TPM are measured by all topologies in floor plans of all cases. Therefore, the similarity scores of two floor plans cannot easily ranking partial similarities or differences between those plans. However, since the metric of every type of spatial topology is cumulated in the system, the ranking of topological weighting among different types of spaces can effectively reduce permutations of different types of spaces. Therefore, it is possible to implement an interface for partial representing of spatial topologies and for retrieving relevant floor plans by the ranking of topological weighting among different types of spaces.

Figure 4 demonstrates the prototype of TPM's interface for retrieving floor plans by partial spatial topologies. However, TPM can only map the topological weightings of all spaces in the query then retrieves the floor plans of cases in the library, and cannot immediately measure similarity score of a new query with all floor plan in the library.

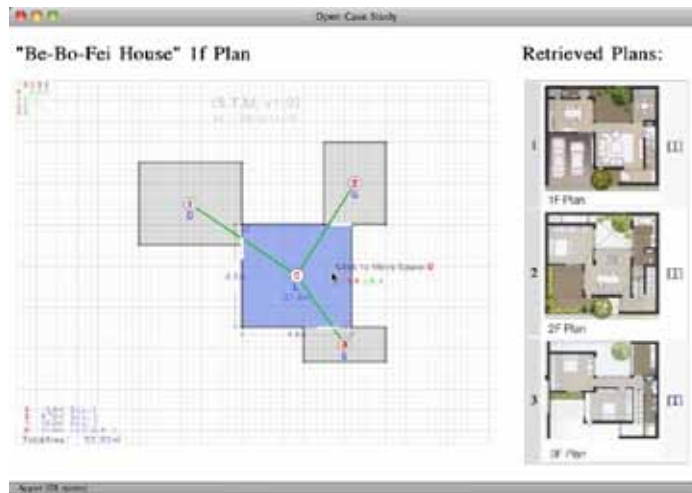


Figure 4. The prototype of STM's interface for retrieving cases by partial spatial topologies.

3.3. THE IMPLEMENTATION OF TPM

OCS is an online case library of house design cases, which is developed in MySQL relational database, PHP script language for server-side data accessing, and JavaScript for client-side interface. TPM extends the abilities of STR from encoding and retrieving spatial topology of individual floor plans, to weighting and ranking similarities among different floor plans.

Just like STR, TPM is developed in Processing - a simplified software IDE developed by MIT (Reas and Fry, 2007). Processing is based on JAVA programming language, but aims to teach fundamentals of the computer programming in the visual art and design education. Via a visual, interactive, Internet-ready interface and the MySQL database connective capabilities of Processing, TPM thereby serves as a visual and interactive tool for retrieving and representing the design patterns of spatial topologies in floor plans of cases within the OCS library.

4. Conclusions

Alexander (1977) proposed the idea of “pattern language” for describing and organizing good design practices of architectural design, and inspired the concept of “design pattern” for many complex engineering tasks such as software engineering. Therefore, for representing design solutions and its problem, a case library can also be an architectural design pattern library. However, because lack of generalizing means for design patterns, the only representation of design pattern in most of case libraries is the case itself. As a result, no case library can provide a mechanism for acquiring then retrieving design patterns.

TPM demonstrates a data-mining approach for detecting the topological features of floor plans, then derive out the patterns of spatial topologies automatically. By applying data-mining algorithms to weight similarity among floor plans of cases, TPM can cluster similar floor plans in order to reveal the patterns of spatial topologies. TPM implements a visual retrieval interface for displaying relevant floor plans of cases based on topological similarity scores and basic geometric features. By applying searching and mapping functions of database technology, TPM can map partial topological layout as a query for retrieving similar floor plans from the library.

However, the data-mining approach is a method that requires a large quantity of calculation. When a new permutation of spatial topologies appears, it needs time to re-measured similarity scores among all cases. Therefore, efficient algorithm for weighting and clustering complex building types will become a challenge for this approach. On the other hand, how to integrate more topological features, such as separating, opening and orientation, and geometric features, such as shape, dimensions and area of individual spaces in the floor plans, into the weighting and clustering algorithm still needs more investigations.

Acknowledgements

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ASSESSING INNOVATION IN HYBRID DESIGNS USING SHAPE GRAMMARS

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Abstract. Al-kazzaz et al (2010) described hybrid adaption technique to generate innovative designs from heterogeneous precedents using shape grammars. An evaluation of the degree of innovation in the hybrid designs gave feedback to grammar users before and after applying a rule. Innovation was assessed using variables derived from the internal structure of the grammar such as: the number of antecedents in the corpus having the same rule; the number of rules in a subclass rule set having the same geometry; etc. However, the validity of the innovation assessment was unclear and the use of the feedback measures was not demonstrated. Accordingly, this study aims to verify the credibility of the innovation measures and to identify the independent variables that a user can control to achieve a significant impact on each innovation measure as a dependent variable.

Keywords. Shape grammars; hybrid design; innovation assessment.

1. Introduction: Assessment methods in shape grammars

In shape grammars, evaluation systems have been used to satisfy different goals. Three approaches can be distinguished according to their roles in the shape grammar process. They are the generating role only, the assessing role only, or both. In the first approach, the problem specific knowledge of design goals is hard-coded in a grammar. The evaluation criteria are added to grammar rules as constraints on the rule selection algorithm to prevent the designers from searching the space of infeasible designs (for example, see Soman et al (2003)). The second approach seeks the optimal design within fixed configurations resulting from applying shape grammars in which the forms of the solutions are known but specific values are needed to be determined, such as in Stiny and Gips (1978). In the third one, combining both the generating and

assessing roles, rules are written to derive valid designs then problem specific models of evaluation criteria are used to search the language for purposeful designs (such as in shape annealing (Shea and Cagan 1998)). Within this approach, Al-kazzaz et al (2010) uses innovation metrics along with rules and grammar to create a powerful feedback mechanism for a grammar user during both the selection of rule and after its application. This paper investigates the validity of the hybrid design innovation measures in Al-kazzaz et al (2010), and identifies the indicators that direct grammar users to obtain hybrid designs with high innovation values.

2. Innovation measures of hybrid design using shape grammars

A hybrid design is an entity that is made up of elements drawn from heterogeneous multiple sources. The main characteristics of a hybrid design are being a mixture of elements of its antecedents on one hand, and having individuality which makes it distinct from its antecedents on the other hand. These characters are translated into innovation measures of hybrid design in Al-kazzaz et al (2010). The independent variables that a grammar user can control in the derivation process are: the number of rules (NR) used to derive the hybrid design, and the rules' evaluation metrics as default values attached to each rule in a grammar to measure the following:

- Rule prevalence value (RPV) is an indicator of the mixed character of a generated design. It is calculated as the percentage of antecedents in the corpus having this rule.
- Rule geometrical difference values (RGDV) and rule sequential difference values (RSDV) are indicators of the individuality of a generated hybrid design. They are calculated as the percentage of antecedents having a different geometry or a different sequence than this rule.

The dependent variables are innovation metrics of mixture and individuality in a generated hybrid design. They are updated values added after rule application at grammar runtime to measure a mixture in terms of variety and density, and individuality in terms of matching and difference, as follows:

- Diversity is a measure of variety in the design mixture. It is calculated as the percentage of antecedents in the corpus having rules in the generated design.
- Abundance is a measure of density of the design mixture. It is calculated as the total average of antecedents in each rule of the generated design.
- Matching is an inverse measure of the individuality in a hybrid design. It is calculated as the higher percentage of applied rules in the generated design belonging to one antecedent in the corpus.
- Geometrical or sequential difference values are direct measures of individuality in a hybrid design. They are calculated as the total average of rule geometri-

cal or sequential difference values in the generated design.

3. Validation of the innovation measures

To verify the validity of the proposed innovation measures, the study compares the innovation values obtained from hybrid designs with ones of copies of antecedents. The ability of metrics to identify that hybrid designs have higher innovation values than copies of existing designs is an index to its soundness. The implementation is done using sample of 12 traditional minaret designs. The hybrid designs are generated according to the method in Al-kazzaz et al (2010). However, to generate a copy of any antecedent, variable state label (n1 or nx) of right hand side of each original rule (OR) is replaced by a state label of an antecedent to be copied. It is one of the constant state labels of left hand side of applied rules, as shown in Figure 1.

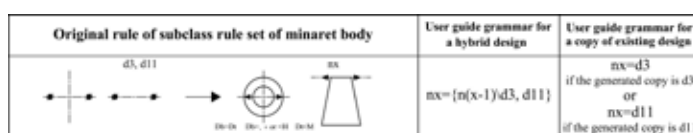


Figure 1: User guide grammar for copies of existing designs and hybrid designs

The study compares the innovation values of 12 copies of antecedents (Figure 2) with 24 hybrid designs: 12 of them are composed of original rules (ORs) (Figure 3), and the other 12 are composed of hybrid rules (HRs) (Figure 4). Each copy of the antecedent has two corresponding hybrid designs created from the same number of ORs and HRs separately.

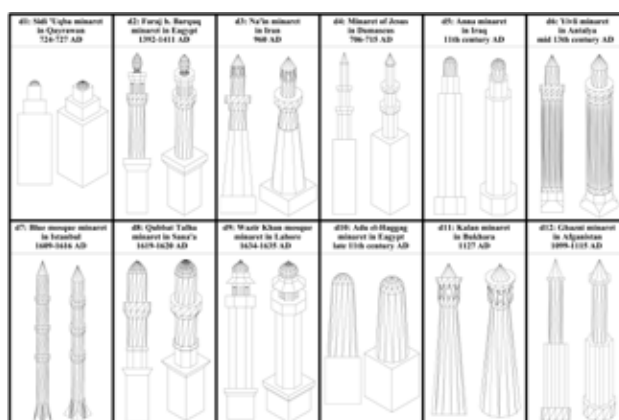


Figure 2: Copies of antecedents in the corpus

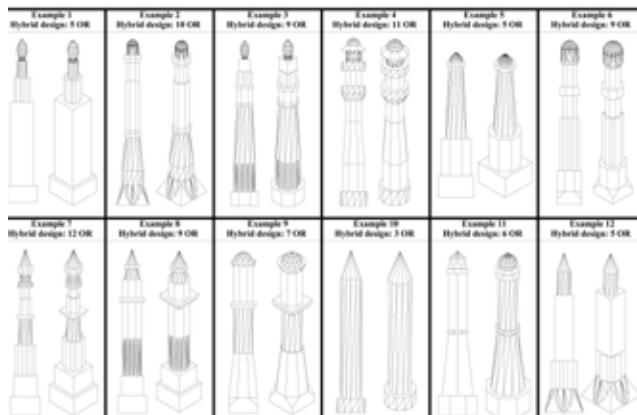


Figure 3: Hybrid designs composed of original rules (OR)

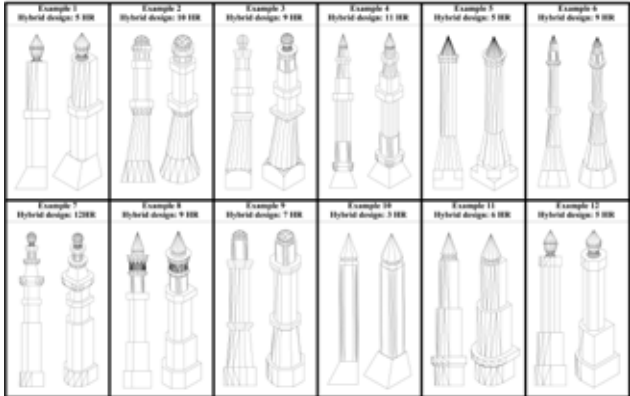
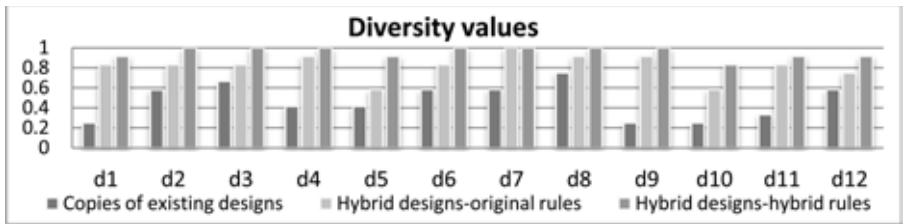


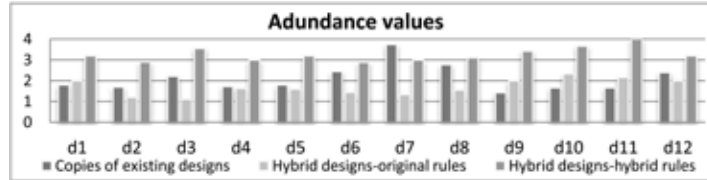
Figure 4: Hybrid designs composed of hybrid rules (HR)

To avoid the effect of the different NRs on the innovation measures, each copy of antecedent is compared with two hybrid minarets having the same number of ORs or HRs. In Graph 1, diversity results show the amount of variety in the mixture of existing and hybrid designs. The diversity of hybrid designs is higher than the copies of antecedents in all of the examined cases.



Graph 1: Comparison between diversity values of copies of antecedents and hybrid designs

The results of abundance values represent the density of the mixture in existing and hybrid designs. Graph 2 shows that 11 of 12 hybrid designs derived by HRs have higher abundance than the copies of existing designs.



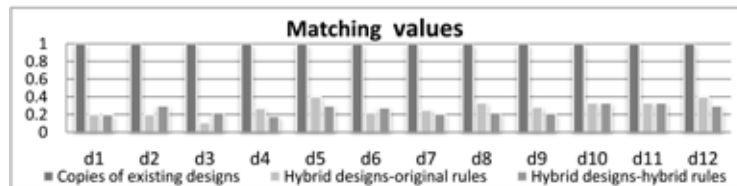
Graph 2: Comparison between Abundance of copies of existing designs and hybrid designs

It is noteworthy to mention that 66.6% of the copies of antecedents have higher abundance values than the hybrid designs derived by ORs. The reason can be attributed to the small percentage (5.5%) of ORs having high RPV which are rules derived from more than 3 antecedents (Table 1). The high abundance of the existing designs such as d7 results from repeating rules with high RPV, in contrast to hybrid design in which the user guide grammar prevents any rule repetition except the cases in which the set of designs in a user guide grammar for hybrid design is $\emptyset$ (Al-kazzaz, Bridges et al 2010).

Table 1: Percentages of the rule prevalence values (RPV) in original and hybrid rules

	High RPV (4-8) labels	Medium RPV (2-3) labels	Low RPV (1) label
Original rules	5.555%	22.222%	72.222%
Hybrid rules	18.888%	74.444%	6.666%

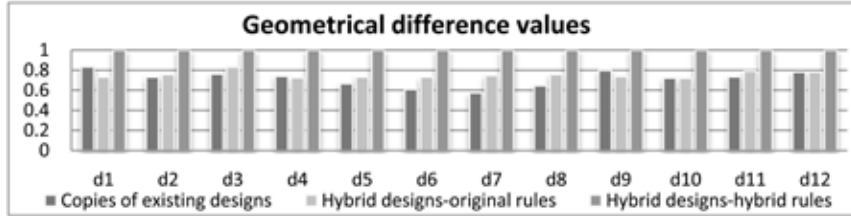
The copies of existing designs have certainly minimum individuality having maximum matching (1) to the antecedents, while the individuality of hybrid designs varied between (0.111) maximum and (0.4) minimum, Graph 3.



Graph 3: Comparison between matching of copies of existing designs and hybrid designs

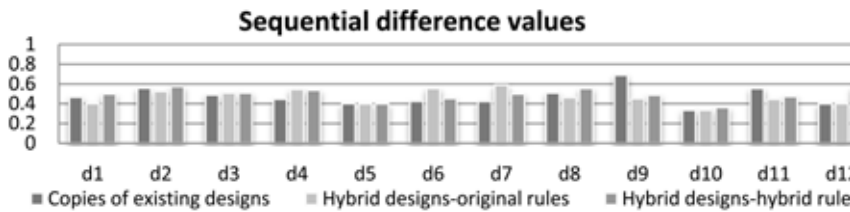
The results of individuality in terms of geometrical difference are presented in Graph 4. They show that all hybrid designs composed of HRs have maximum geometrical difference value (1). Additionally, in 7 of 12 cases, the hybrid designs composed of ORs have geometrical difference values higher than the

copies of antecedents, and in two cases their geometrical difference values are equal.



Graph 4: Comparison between GD values of copies of existing designs and hybrid designs

Lastly Graph 5 shows small variance in the sequential difference values between copies of existing designs and both hybrid designs. Even so, in nine cases, the values of sequential difference of hybrid designs (original or hybrid rules) are higher than those of copies of existing designs.



Graph 5: Comparison between SD values of copies of existing designs and hybrid designs

In conclusion, comparing the innovation measures of both the mixture and individuality in the generated designs reveal that the values of hybrid designs are higher than the copies of antecedents. This result confirms that the assessment method is able to find differences between copies of antecedents and hybrid designs which is regarded as a proof of its validity as innovation measures of the hybrid designs. The other concern of this paper is to identify the factors which the grammar user can take into account to direct the generated hybrid design to have high innovation values.

4. Factors affecting the innovation of hybrid design

Being a mixture and having individuality are the innovation characteristics of the hybrid designs measured by diversity and abundance for the former, matching and geometrical and sequential differences for the latter. They are dependent variables affected by the independent variables which a grammar user can control such as: rule prevalence (RPV), rule geometrical difference (RGDV), rule sequential difference (RSDV), and the number of rules (NR) used to derive a hybrid design. The initial expectations of the relations are:

- High NR may have a positive effect on the variety of the design mixture.
- High RPV may affect positively the variety and density of the mixture, while it may affect negatively the individuality by increasing the matching degree.
- High RGDV and RSDV have definitely a positive effect on individuality by increasing the geometrical and sequential difference of the generated design.

The first two assumptions need to be verified, while the third has no need because it is inevitable. Therefore, the study concentrates on examining the relations between the innovation metrics and each of the NR and RPV.

Correlation coefficients have been calculated to measure the effect of changing the NR and RPV on each of the dependent variables in 12 copies of existing designs and 24 hybrid designs derived in the previous stage. The results are presented in Table 2 which shows predictive relations such as:

- Relation type: (+) means direct, (-) means inverse, or (0.0) means no relation.
- Relation strength: (0.7-1) is strong, (0.4-0.7) is moderate, or (0-0.4) is weak.

Table 2: Correlation coefficient values between innovation measures and each of NR and RPV in copies of existing designs CED and hybrid designs HD using OR and HR

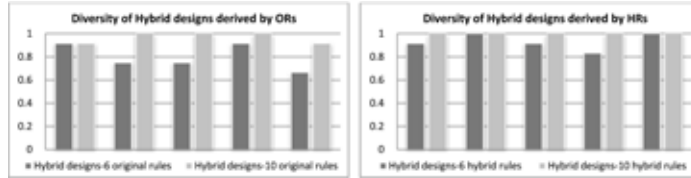
		Innovation measures				
		Diversity	Abundance	Matching	Geo. difference	Seq. difference
CED	NR	+0.589	+0.519	0.0	-0.47	+0.232
	RPV	+0.662	+0.997	0.0	-0.72	-0.353
HD-OR	NR	+0.786	-0.781	-0.5	+0.114	+0.96
	RPV	-0.363	+0.996	+0.592	-0.299	-0.77
HD-HR	NR	+0.887	-0.562	-0.565	0.0	+0.551
	RPV	-0.649	+0.919	+0.418	0.0	-0.553

The results reflect differences between existing and hybrid designs. Some results of hybrid designs are contrary to expectation and need more investigation, such as the inverse relations between the RPV and diversity values.

Accordingly, the research aim is to verify the effects of each predictor variable: NR and RPV on innovation measures of mixture and individuality in hybrid designs. Both variables can direct a user to generate hybrid designs with high innovation. To reduce the mutual influence of the NR and RPV on each other, the research derives 10 pairs of hybrid designs, 5 of them using ORs and the others using HRs. Each pair consists of hybrid designs having 6 and 10 rules derived from the same (4-5) rules to reduce the effects of varied RPV. In this case, the comparison between designs of 6 and 10 rules in each pair reveals the impacts of different NR on the innovation measures. On the other hand, comparison between hybrid designs composed of 6 or 10 rules separately, explains the effects of various RPV on the innovation measures.

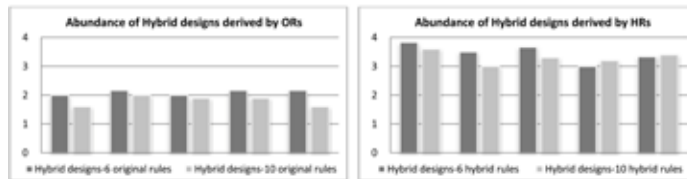
5. The effects of NR and RPV on the innovation of hybrid designs

The effects of NR on diversity, as shown in Graphs 6 and 7, reveal that all hybrid design composed of 10 rules have either equal or higher diversity than hybrid designs composed of 6 rules. These results are compatible with their strong direct relations concluded in Table 2.



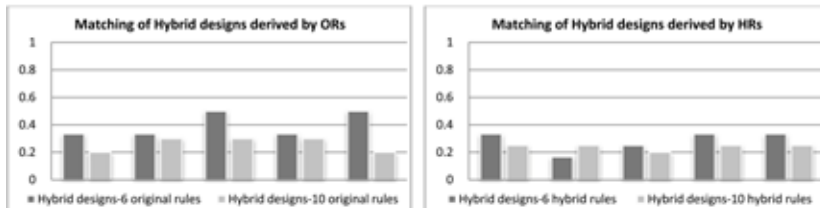
Graph 6 (left) and Graph 7 (right): Diversity values of hybrid design

The results of abundance values in Graphs 8 and 9 show that all hybrid designs composed of 6 OR have higher values than hybrid designs composed of 10 OR. In addition, half of hybrid designs composed of 6 HR have higher abundance than designs composed of 10 HR. The results are compatible with the strong and moderate inverse relations, concluded in Table 2, which are attributed to the higher average of RPV in designs of 6 rules than 10 rules.



Graph 8 (left) and Graph 9 (right): Abundance values of hybrid design

The matching results in Graphs 10 and 11 reveal that all hybrid designs composed of 6 OR have higher matching values than ones composed of 10 OR. Also, in 4 of 5 cases, the matching values of hybrid designs composed of 6 HR are higher than those composed of 10 HR. These results refer to strong inverse relations between matching values and NR, and have some differences than the moderate inverse relations shown in Table 2.



Graph 10 (left) and Graph 11 (right): Matching values of hybrid design

The design geometrical and sequential difference values are innovation metrics of individuality in hybrid design. They are fully influenced by rule geometrical difference (RGD) and rule sequential difference (RSD) values. Thus, there is no need to investigate the effects of the RN and RPV on them. On the other hand, the results of correlation coefficient between the average of the RPV and both diversity and matching values show some random relations which varied between weak and strong. In addition, all diversity values of hybrid designs composed of 10 HR are 1.0, therefore there is no correlation relation with RPV. These results reveal that the RPV factor alone is not enough to indicate the diversity and matching as the innovation measures of variety and individuality in the mixture of generated hybrid design. Lastly, the correlation coefficient between abundance values and RPV reflects strong direct relations for all hybrid designs derived by (6 and 10) ORs and HRs. The abundance outcomes are consistent with the results in Table 2.

6. CONCLUSION

The study has sought to achieve two objectives. Firstly, it is to verify the innovation measures of mixture and individuality in the hybrid designs. The ability of these measures to distinguish between copies of existing designs and hybrid designs is the test of their validity. The results show that most hybrid designs have higher innovation metrics than the copies of antecedents. Accordingly, the validation of these measures is verified.

The second aim is to highlight the signals of grammar user feedback that contribute efficiently in deriving hybrid design with high innovation values. The study focused on two independent variables: the number of rules (NR) used to derive a design, and the rule prevalence value (RPV); and three dependent variables of innovation metrics: diversity, abundance and matching.

High NR enhances the diversity of the mixture in hybrid designs composed of ORs and HRs. In contrast, the high NR may affect negatively the abundance value which represents the density of the hybrid design mixture. The reason can be attributed to the fact that a grammar, because of the heterogeneity of antecedents in corpus, has a limited number of rules with high RPV (Table 1). Accordingly, the percentage of rules with high RPV is more likely higher in designs having few rules than many rules. Lastly, high NR strengthens the design individuality by decreasing the matching degree. It can be justified, to some extent, for the same reason mentioned above.

The relations between RPV and innovation measures are random in case of diversity and matching. In contrast, high RPV boosts the abundance measure of density in the mixture of hybrid design. The reason why the applied rules with high RPV may not enhance the diversity values can be attributed to the

fact that the applied rules have some common antecedents in their state labels. Additionally, this reason is more likely to raise the matching value. These results revealed the need to add indicators to represent the dependency of diversity and matching values on RPV. Diversity and matching indicators are two updated values added at grammar runtime beside the LHS state labels of each rule. Diversity indicator calculates the percentage of rule antecedents in the user guide grammar. While, matching indicator calculates the percentage of rule antecedents that do not exist in the user guide grammar. For example, if the set of antecedents in the user guide grammar is {d2, d3, d6, d9, d12}, then the diversity indicator of a rule having LHS state labels {d3, d4, d9} is $2/5=0.4$, and the matching indicator is $1/3=0.333$.

Based on the results, a key for rule selection is shown in Figure 5. The effects of the varied NR to the number of existing designs in the corpus (D): ($NR < 0.5D$, $NR = D$ or $D > NR > 0.5D$) and the varied RPV: (high, medium or low) on the innovation measures: diversity, abundance and matching are extracted. The grammar user can follow the tactics to derive hybrid designs with high innovation values and can distinguish the rules (original or hybrid) that meet the required level of innovation measures (high, medium or low).

		High Rule Prevalence Value State labels $> 0.25 D$			Medium Rule Prevalence Value $0.25 D \geq$ State labels > 1			Low RPV 1 State label
		All LHS labels C (nx-1)	Some of LHS labels C (nx-1)	One of LHS labels C (nx-1)	All LHS labels C (nx-1)	Some of LHS labels C (nx-1)	One of LHS labels C (nx-1)	One LHS label C (nx-1)
Hybrid designs Original rules NR=D	NR<0.5D	●	●	●	●	●	●	●
	NR=0.5D	●	●	●	●	●	●	●
	NR>0.5D	●	●	●	●	●	●	●
Hybrid designs Hybrid rules NR=D	NR<0.5D	●	●	●	●	●	●	●
	NR=0.5D	●	●	●	●	●	●	●
	NR>0.5D	●	●	●	●	●	●	●
		● High Diversity	● High or Medium Diversity	● Low Diversity	■ High Abundance	■ Medium Abundance	■ Low Abundance	▲ High or Medium Matching
					▲ High Matching	▲ Medium Matching	▲ Low Matching	

Figure 5: The effects of RPV and NR on innovation measures of hybrid designs

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AGENT-AGENT INTERACTION AS A COMPONENT OF AGENT-ENVIRONMENT INTERACTION IN THE MOD- ELLING AND ANALYSIS OF PEDESTRIAN VISUAL BEHAVIOUR

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Abstract. This multidisciplinary project involves concepts from architectural design, statistical learning, machine vision, and human ecology. The focus is on analysing how pedestrians' dynamic behaviour in space is influenced by the environmental design of different architectural scenarios. This paper presents a multi-agent pedestrian simulation and analysis system that supports agent-to-agent interactions, different spatial desires, and interpersonal distance. The system simulates and analyses pedestrian spatial behaviour with combined focus on movement trajectories, walking speed, and the visual gaze vector. The analysis component relies on learning a statistical model characterising normal/abnormal behaviour, based on sample observations of regular pedestrian movements without/with the impacts of significant visual attractions in the environment. Using the example of Wheeler Place in Newcastle (Australia) our pilot experiments demonstrate how pedestrian behaviour characteristics can depend on selected features in the visual environment. The presented system will allow architects and urban designers to obtain better assessment of planned urban spaces and streetscape characteristics and their impacts on pedestrian behaviour.

Keywords. Agent interaction; pedestrian behaviour; analysis.

1. Introduction

Environmental perspective is an extremely important viewpoint of human spatial behaviour analysis. This view assumes that the physical characteristics

of an environmental setting influence our attitudes and actions more than a biological or cultural trait. Spatial behaviour modelling focuses on the visible, *static* and *dynamic* properties of the physical environment as important factors, since socio-cultural variables are harder to measure and less obvious across behavioural settings. Analysing this behaviour in indoor and outdoor areas is an important facet of architectural and urban design.

The simulation of pedestrian behaviour allows us to investigate spatial visual behaviour without the difficulties of real-world data analysis. Planning pedestrian environments requires assumptions about how real pedestrians will respond to characteristics of the planned environment. Placing virtual pedestrians in architectural space simulation significantly aids in making the assumptions more real (Thiele, 2002).

A number of methodological approaches have been proposed to model pedestrian behaviour: *Analytical models* (Antonini et al, 2006, Ness et al, 1969), *Cellular automata* (Francesca Camillen et al, 2009, Wang and Chen, 2009), and *Agent based simulation* (Bonabeau, 2002, Francesca Camillen et al, 2009, Yannis and Golias, 2009). Advantages and disadvantages of using each method and a more detailed literature review of the proposed pedestrian behavioural models have been discussed in our previous works (Jalalian et al, 2011).

Representation of the physical space plays a central role in modelling pedestrian spatial behaviour. In “public” places, including external environments (streets and plazas) and internal spaces (malls and museums), “attractors”, like billboards or display stands or even a group of people, can distract pedestrians from following a direct path towards their destinations. While there are a range of possible names for these visual distractions, we describe them as “attractive objects”. In urban spaces the attractive objects have different *conspicuity* areas (Yantis, 1998). For instance a high-rise tower in the centre of a town may attract more attention from greater distance than a poster on a nearby wall (Ratti, 2004). Previously we have taken the variety of conspicuities into account by defining different “levels of attraction” for attractive objects (Jalalian et al, 2011, Jalalian et al, 2010).

In the present paper we propose an innovative approach to equip simulated objects with *dynamic* levels of attraction. Pedestrian-environment interactions in parallel with pedestrian-pedestrian interactions have significant impact on pedestrian spatial behaviour and walking patterns (Baldassare, 1978). Since vocal interactions are harder to measure and depend on many geometrical and cultural variables, we focus on the visual part of pedestrian-pedestrian interactions. We investigate the dynamics of human head pose and eye gaze behaviours which can provide significant insight into the context of a spatial

behaviour. It has been shown that gaze direction and eye contact are essential features of group communication, as they help to elicit behavioural characteristics from others (Doshi and Trivedi, 2009, Argyle and Dean, 1965, Kendon, 1967, Ballerini et al, 2008).

Sudden changes in gaze direction may or may not be linked with attractive objects. A substantial amount of research in psychology has examined whether such behaviour is caused by internal stimuli (such as changing the route) or by external stimuli (Itti and Koch, 2000, Peters and Itti, 1999, Navalpakkam and Itti, 2005, Rothkopf et al, 2007). While attractive objects take up a significant portion of visual external stimuli, other peoples' gaze direction could be considered as another important category of external stimuli to attract a pedestrian's gaze (Yantis, 1998). As the number of people looking at an attractive object increases, the object can attract more attention. The presented system incorporates our previously proposed pedestrian simulation system (Jalalian et al, 2011). The new system described in this paper, has been designed to support pedestrian-pedestrian visual interaction and models the impacts of eye interactions in changing pedestrian spatial behaviour. The purpose of the simulation is to model and analyse this spatial behaviour in order to have a better assessment of a planned urban design and its impacts on pedestrian behaviour.

2. Simulating pedestrian visual attention

The simulation generates a set of behavioural characteristics – for example walking, running, standing, getting attracted to an obstacle, and associated changes of the gaze direction. Our analyser software evaluates the simulated behaviours in order to identify the impacts of different walking environments on pedestrian behaviours.

2.1 ATTENTION AND EYE MOVEMENTS

The fact that eye movements are linked by attention doesn't mean that these two systems are completely mutually dependent. (Helmholtz, 1962) confirms that observers can direct their visual attention to different areas of visual space even while the eyes remain fixed. Thus the relationship between attention and eye movements is one of partial interdependence. Attention is free to move independently of eyes, but eye movements require visual attention to precede them to their goal (Hoffman, 1998).

While pedestrians are walking in an urban space their eyes scan their surroundings using saccadic eye movements. Saccadic eye movements occur at rate of about 3-4 per second (Becker, 1991). The eyes are essentially blind

during these movements and the information from the scene is acquired only at fixation points. (Yarbus, 1967) pointed out that the location and sequence of saccades is not completely random. Eye movements from one fixation point to another are fast enough that in the simulation, we can assume that all the objects in certain range are scanned during a timestamp (4 seconds). The range of this scan varies from one person to another (Klein and Pontefract, 1994) and it mainly depends on the location that the pedestrian is looking at while walking. This is modelled by defining different effective ranges for “useful field of view” (UFOV) (K. Ball and Owsley, 1991). In the initial stage of the simulation a *sight category* is assigned to each agent. The sight category is a random number which limits the minimum and maximum range of UFOV. The number of sight categories can be defined and changed by the user in the provided *user interface* of our analyser software.

2.2 GOAL-DRIVEN VS. STIMULUS-DRIVEN ATTENTION

According to (Yantis, 1998), visual attention is either goal-driven or stimulus-driven. Attention is said to be goal-driven when it is controlled by an observer’s intention and needs. For instance if the observer is hungry and looking for food, automatically all the food shops will direct his attention. In the simulation, pedestrians’ goal-driven attentions are modelled by the “agent need vector” (ANV) and the “object category vector” respectively. These vectors are assigned to agent and object at the initial stage. Each element of the ANV reflects a category of need for the agent. The value assigned to each element expresses how desperate the agent is to satisfy that particular type of need. In the object category vector each element expresses how much the object is able to satisfy an agent’s need.

In contrast, stimulus-driven attention is controlled by visual attributes of the object that are not necessarily relevant to the observer’s perceptual goal. In the previous example, if all the food shops tended to be fast food restaurants, then a single Persian restaurant among them would capture the observer’s attention automatically. Stimulus-driven attention is modelled by the “object level of attraction”. A bigger value for the object level of attraction means the object has a stronger impact on an agent’s attention.

2.3 CROWD ATTRACTION AS A VIRTUAL ATTRACTIVE OBJECT

The social group is a fundamental and universal feature of human social life. Group formation is the expansion of bonds of interpersonal attraction due to the existence of common desires among individuals (Hogg, 1985). Having the same goal-driven attentions could be considered as one of the major deter-

minants of group formation in urban environments (Carwright and Zander, 1968). In our simulation we assume that agents who are visiting the same attractive object can form a group.

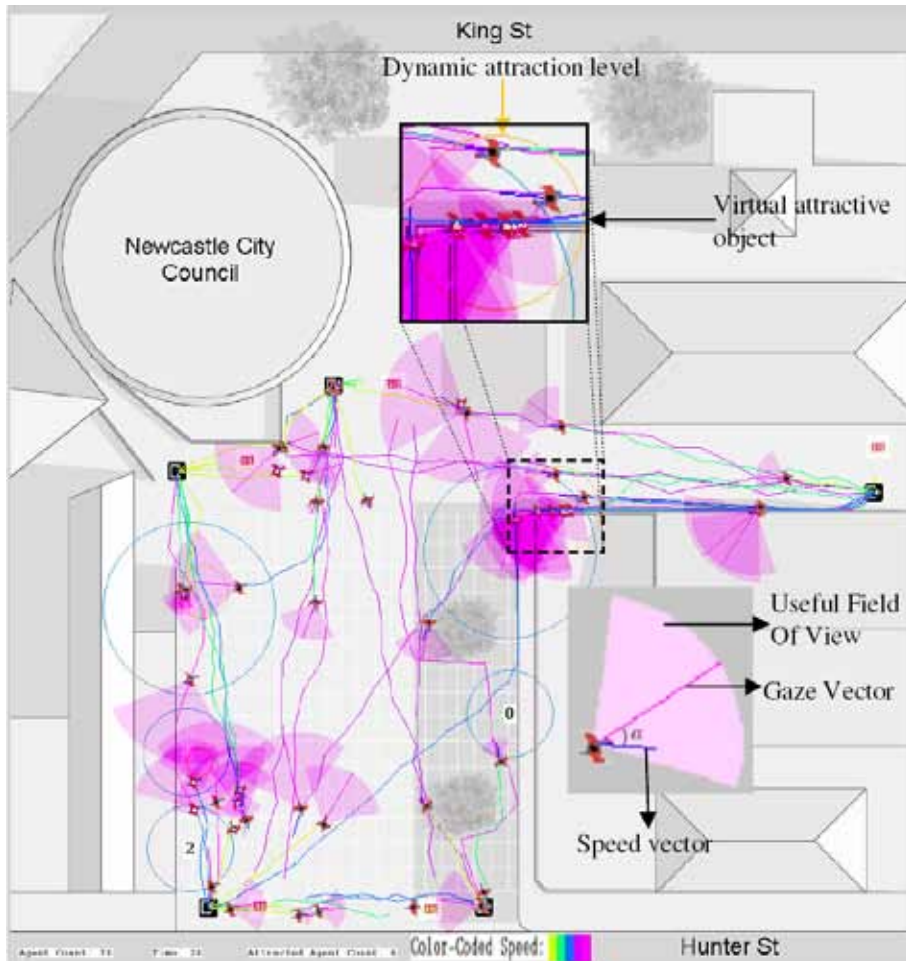


Figure 1. Wheeler Place simulation in scenario2

Group size is an important variable for capturing attention: Large groups are able to draw more attention than small groups. In order to model how *group formation* and *group size* impact on pedestrian spatial behaviour, we consider a group of people as an attractive object with a *dynamic* attraction level and call it a *virtual attractive object* (Figure 1). A virtual attractive object (VAO) has the same feature set as an *actual attractive object*. However, in the case of VAOs, the location and level of attraction vary according to the location and

number of agents in the group. As agents are walking in the scene they may get attracted to a selection of attractive objects (virtual or actual). The selection depends on agent needs, agent location, sight category, UFOV, object location, object category, and crowd locations. Agents consider attractive objects as temporary destinations. Once they finish visiting the attractive objects they will continue their way towards exit points.

2.4 OBJECT SELECTION PROCESS IN THE SIMULATION

Attractive object selection starts by calculating the distance of agent's **UFOV** and the level of attraction of all the attractive objects that the agent can see. Among the objects, the one which minimises this distance is the "best object". We assume that actual attractive objects have higher priority than VAOs. Therefore the search for finding the "best object" is done over the real objects first, then over virtual objects.

Once the "best object" is found, the *Euclidean distance* between the ANV and object category vector is calculated. If this distance is less than a *threshold* it means that the agent likes/needs the object and its state will be changed to "becoming attracted", otherwise it will be changed to "not becoming attracted". Agents show the same behaviour if the selected object is a VAO, but instead of studying the object it will join the group and this will increase the level of attraction of the VAO.

3. Agent behaviour analyser

In order to analyse pedestrian behaviour, we have previously proposed and applied a new approach for outlier detection of pedestrian spatial behaviour (Jalalian et al, 2010). Our system analyses pedestrian behaviour with a combined focus on agent location (x_t, y_t), direction of movement (β_t), speed $\frac{T_t \cdot l}{\|r_t\|}$, the angle between direction of movement and gaze vector (α_t) and the angular velocity ($d\alpha_t / dt$) associated with the gaze vector of individuals in large groups of simulated pedestrians. The system learns a statistical model characterising normal behaviour, based on sample observations of regular pedestrian movements without the impact of significant visual attractions in the environment. Irregular pedestrian behavioural characteristics, mainly caused by detection of visually attractive objects, are considered as abnormal behaviour. We employed one-class support vector machines (SVMs) (Schoelkopf et al, 2001) combined with Dynamic Time Warping (DTW) (Keogh and Pazzani, 2001) to separate agents into two classes; *attracted agents* and *normal agents*.

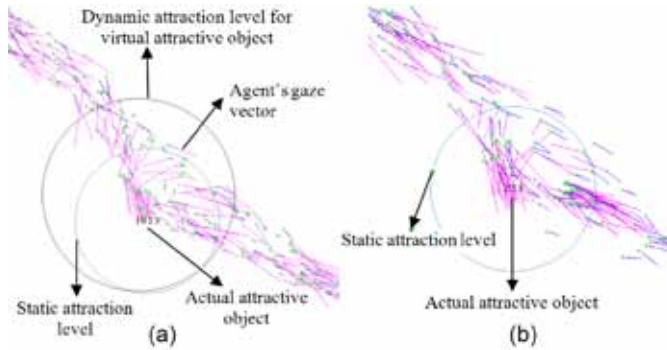


Figure 2. Agent's behavioural characteristics with (a) and without (b) the impact of a VAO

4. Experimental results

The new software system runs a pedestrian simulation on a plan of Wheeler Place. We have selected this place because: The space is next to Newcastle's Civic Theatre and City Council Chamber. These two buildings have made this area one of Newcastle's most crowded public spaces. Here *crowd attraction* is a common behaviour, and there are several places of different levels of attraction such as the City of Newcastle Information Centre and Climate Meter, Juicy Beans Restaurant and Internet Cafe, a big public art work, the Civic Theatre and Civic Theatre Restaurant.

Figure 2(a) shows the impact of "dynamic attraction level" on agent trajectory. Agents who are looking at an attractive object may form a group and this is shown as a virtual attractive object. The level of attraction of a virtual attractive object changes according to the number of agents in the group. Agents can be distracted by VAOs as well as by actual attractive objects. As shown in Figure 2(b) some agents who have a small *sight value* might miss the attractive object. In Figure 2(a) the dynamic level of attraction is large enough to direct all agents' attention and therefore all agents can see the attractive object. Agents' behavioural response to virtual attractive objects models pedestrian behaviour in the real world where crowd attraction is a significant component of visual behaviour.

Figure 3 illustrates typical simulated behavioural characteristics of an agent with and without the impact of VAOs. It shows the speed of movement ($\|s\|$) and the speed of the angle between the movement direction and gaze vector (da/dt). The period that the agent was attracted by an attractive object is called the visiting period. Just before this period there is a "becoming attracted" period. In this period the agent moves towards the object with

the highest allowed speed defined in its speed category (see the black curve in Figure 3). Agents might turn their attention to the VAOs prior to the actual ones. The patterned area in Figure 3 represents this behaviour. As shown in this figure (da/dt) shows significant change once an agent's attention is directed to a virtual/actual attractive object. This describes a pedestrian's behaviour when he suddenly changes his gaze to a visually attractive object. Our proposed analyser can detect this behaviour.

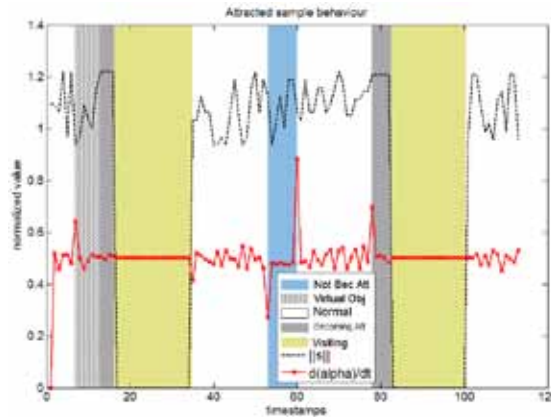


Figure 3. Simulated behavioural parameters; becoming attracted to a virtual attractive object (patterned area), becoming attracted to an actual attractive object (grey area), visiting period (green area), and attention without becoming attracted (blue area)

Table 1 Average probability of attraction

VAO	ANV	SC1	SC2	SC3	SC4	SC5	SC6	SC7	SC8	SC9	SC10
NO	NO	0.49	0.52	0.46	0.47	0.47	0.45	0.46	0.47	0.44	0.45
NO	YES	0.25	0.26	0.24	0.19	0.25	0.22	0.24	0.25	0.18	0.21
YES	NO	0.54	0.57	0.52	0.53	0.55	0.51	0.54	0.54	0.50	0.52
YES	YES	0.24	0.32	0.30	0.25	0.24	0.27	0.24	0.23	0.29	0.23

In previous work we defined 10 possible scenarios (SC1-SC10) that were considered in our simulation experiments of Wheeler Place. The scenarios describe the permutations of the positions of five selected attractive objects (blue circles in Figure 1) (Jalalian et al, 2011). In the present paper we employed them again with the new system to show the effects of VAOs and ANVs on the number of attracted agents. Table 1 shows the average probability of attraction for different positions in different scenarios with respect to the number of simulated agents. The results in this table were obtained from simulating 5000 pedestrians for each scenario. These results suggest three conclusions: 1) The

introduction of ANVs always decreases the average probability of attraction. II) The introduction of VAOs (i.e. step from row 1 to row 3 or from row 2 to row 4 in Table 1) Increases the average probability of attraction in the absence of ANVs for all scenarios. However, in the presence of ANVs this increase was not consistently observed. III) Scenario 2 (shown in Figure 1 and SC2 in Table 1) has the highest probability of attraction independently of the presence or absence of VAOs or ANVs. Our pilot experiments also confirm that if we increase the number of agents in the scene, the average probability of attraction will be increased. This clearly shows the impact of crowd attraction on pedestrian spatial behaviour.

5. Conclusion

In this paper the dependency of attention and visual gaze direction was discussed. We have proposed and tested an innovative model to simulate goal-driven attention and stimuli-driven attention with the “agent need vector” (ANV) and the “object level of attraction”. The proposed model includes “group formation” and the effects of “group size” on directing pedestrian’s attention. The simulation was run for a real-world space, Wheeler Place in Newcastle. Different scenarios with different configurations and the impacts of considering crowd attraction on pedestrian behaviour were presented and discussed. The experimental results demonstrate that the new system can provide significant support for understanding how changes in the configuration of the physical/visual built environment are reflected by measurable changes in agent behaviour.

Acknowledgement

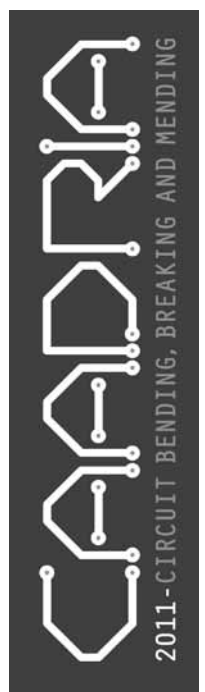
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COMPUTATIONAL RESEARCH IN DESIGN EDUCATION



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54.	Gains, losses and limitations in designing parametrically: A critical reflection of an architectural design studio in China <i>Christiane M. Herr</i>	569
55.	The Headspace project: Computer-assisted fabrication as an introduction to digital architectural design <i>Stanislav Roudavski and Anne-Marie Walsh</i>	579
56.	The social network virtual design studio: Integrated design learning using blended learning environments <i>Marc Aurel Schnabel and Jeremy J. Ham</i>	589
57.	Thinking through digital simulation tasks in architectural education <i>Matthew Fraser and Michael Donn</i>	599
58.	Impact analysis of digital-based architecture curriculum on students' learning <i>Rabee M. Reffat</i>	609

GAINS, LOSSES AND LIMITATIONS IN DESIGNING PARAMETRICALLY

A critical reflection of an architectural design studio in China

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Abstract. This paper argues that learning to design parametrically in the architectural studio entails gains but also losses, since the parametric design approach tends to and encourage certain patterns of thought while discouraging others. This investigation complements previous research focusing mostly on technological aspects. Based on observational data from a parametric design studio in China, this paper discusses how parametric designing can pose challenges to existing design values and approaches, specifically within a Chinese context. It further draws attention to the limitations of parametric designing, which in the observed cases required both students and teachers to break and extend parametric models besides and beyond parametric variation to make them work architecturally. This paper aims to inform educators employing parametric designing in their architectural design studios as well as researchers who examine such studios.

Keywords. Parametric design; studio; design culture; education.

1. Introduction

Parametric designing has become central to international architectural discourse, both in theory, practice and education, as demonstrated by the series of Smart Geometry conferences and workshops. Following the example of several leading design schools, such as the Architectural Association in London, many schools of architecture internationally are introducing, or have recently introduced, parametric design tools and related design approaches to their design studios. Parametric designing hinges mostly upon the use of

parametric software tools and promises architects “new degrees of freedom in aesthetics, processes and structural design” (Anders 2003). As Kolarevic (2003, p.27) suggests, the parametric approach to design “profoundly changes the entire nature and the established hierarchies of the building industry, as well as the role of the architect in the processes of building”. In addition to its modelling capacities, the potentials offered by parametric designing when integrated with fabrication or BIM has been demonstrated by a range of papers previously presented at CAADRIA.

Beyond the scope of a set of software tools or modelling techniques, parametric designing has also come to be understood as a distinct architectural design approach. In his ‘Parametricist Manifesto’ Schumacher (2009) claims that parametric designing has inspired a new movement characterised by “radically new ambitions and values” (ibid., p.15). In a normative manifesto style, Schumacher (ibid.) advances several imperatives of parametric designing, centred around the articulation of programmatic, institutional and social complexity: According to Schumacher (ibid.), a designer with “parametricist sensibility” emphasises variety and continuous differentiation through establishing relational systems, and pursues elegance as ordered complexity. Rigid geometric primitives and the simple, unmodified repetition of elements as found especially in Modernist design, are to be avoided. Schumacher’s propositions have been subject to considerable debate demonstrating how ideologically charged parametric designing may be.

Previous case studies in design-educational studio contexts have typically reported on the potentials and techniques of modelling form through topological models (see for example Schnabel 2006, Hewett and Burke 2010), and on ways of linking parametric designing to fabrication (see for example Bechthold 2007). But in addition to such gains and potentials, parametric designing must realistically also be assumed to imply limitations - as any other design approach pursued in exclusivity. Snooks (2011) for example argues that parametric tools may be useful in design development, but not necessarily useful in sketch design or early stages of a project. Iordanova (2007) and Iordanova et al (2009) are among only few studies examining parametric design in the architectural design studio discussing challenges in teaching this subject. Many open questions remain: What are these limitations and how do students and teachers deal with them? How can parametric designing be integrated with other design approaches in the design studio? How does the introduction of parametric designing and related design criteria relate to the contexts of different design cultures and values? This paper investigates qualitatively an architectural design studio project in which parametric designing was introduced to students to whom the approach was new. It reports and discusses

observations made over the course of the studio in terms of the gains, losses and limitations experienced by involved students and teachers.

2. Introducing parametric designing to an architectural studio in China

The studio presented in this paper was held at Shenzhen University in 2009/2010. It lasted for one semester and included the semester break, a total of 24 weeks. Twenty students from mixed undergraduate years (mostly third year students) were working in design teams of four. The studio was co-taught by two Western teachers (one of which being the author) in English language tutorials and critiques. Most participating students had not been taught by foreigners before, and had limited knowledge of CAAD. The design brief for the studio called for a mixed-use high-rise building to be designed within an urban village in Shenzhen, which required students to reconsider the typology of conventional high-rise buildings to accommodate the surrounding urban village context. As part of the studio, students were introduced to both Rhinoceros 3D and parametric modelling in Grasshopper, which students were required to try but not necessarily to rely on exclusively. Figure 1 illustrates examples of design works resulting from the studio. Outcomes of the studio were presented to and discussed with international guest critics in three design critiques and shown in a final exhibition.



Figure 1. Parametric design proposals for a mixed-use highrise in Shenzhen, China.

Throughout the studio, observational data was collected in multiple formats for qualitative analysis, including student comments in open-ended questionnaires, transcripts from design critiques, field observation notes as well as photos, drawings, posters and presentation materials. The data analysis

process proceeded according to the grounded research methodology following Glaser (1998). A grounded research approach similar to Herr and Karakiewicz (2008) was chosen as it allows for the construction of explanatory models from progressive coding of various kinds of qualitative observational data with minimal influence of existing models. Collected data was examined with special focus on aspects of creativity, significant personal experiences and values as expressed in the comments of involved students, critics and teachers. I argue that this aspect has so far been under-represented in mainly quantitatively and technologically focused previous work and may be of value to educators involved in digital design research and teaching, in particular those teaching in Asian, and especially Chinese, contexts. The analysis process of observational data resulted in a descriptive framework of students' learning processes in relation to teachers' and critics' requirements in this particular studio. The analysis further suggests new questions that may inform similar educational research in the future. In the following sections, observations are summarized under four main guiding questions which structured and guided data analysis.

3. Were parametric models used for generating ideas early on?

Parametric modelling requires designers to develop geometry in terms of hierarchical and logical relationships of "parametric schemata" (Woodburry 2010). As Iordanova (2007) notes, learning to design parametrically from scratch is difficult and can be aided by providing a library of case studies or "referents" to aid students in quickly building up own parametric models by adapting and integrating existing parametric models. In the design studio discussed in this paper, students initially worked from (non-parametric) diagrams that connected site analyses to design proposals. These diagrams were developed in ongoing processes, in parallel to and supporting the development of design ideas. As students' conceptual idea diagrams kept changing, often dramatically, questions regarding building form were not decided upon in the first half of the design studio. Only when diagrams were reasonably consolidated, commitments to topological forms were agreed upon within the design teams, which could then be modelled parametrically. Parametric variation of form thus happened only in the last phase of the design process. Students described their use of parametric designing as helping to "realise" their ideas, not as supporting idea development. This matches with Snooks' characterization of parametric design tools as primarily useful in "design development" yet not in "conceptual development". One student group commented in an interim design critique: "We have an image in our mind. It has its logic mostly about the space. But it is different from Grasshopper logic, which is more

about data. When we translate it into Grasshopper, generally we cannot get a satisfying result.” In analogy to Iordanova’s (2007) use of referents, students of this studio tended to make use of referents, too – although these were not parametric models but diagram formats. Figure 2 illustrates similar diagram formats used by different groups, adapted from the analytical visualisation of functions as for example used by OMA in the design of the Seattle public library. In both cases shown in Figure 2, the diagrams served idea development purposes but did not determine the final building forms.

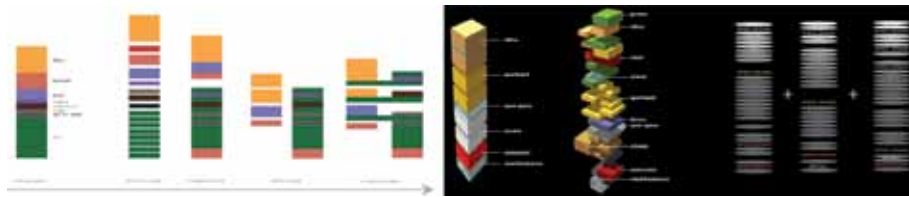


Figure 2. Diagrams for idea development in two different groups based on OMA's Seattle Public Library design, preceding the parametric design process.

Based on these observations, the variety and differentiation enabled by parametric modelling, as emphasised by Schumacher (2009), seems to affect only a limited part of the architectural model: it allows variations of parametrically defined shapes but the topological structure of the model remains largely unaltered. This may explain the observation that students preferred to work with diagrams while they were still reconsidering the topology of their architectural proposals, and only committed to parametric models (and variation of geometric form facilitated thereby) once a topology was agreed upon.

4. When was parametric designing used, and when were parametrically designed results fundamentally revised or abandoned?

Student questionnaire feedback as well as field observations indicate that students integrated parametric designing into a wide variety of design approaches. Among the approaches deployed were sketches, physical models, digital parametric and conventional models in various digital modelling tools, diagrams as well as visual programming in Grasshopper. Iordanova (2007, p. 688) acknowledges that architecture may be too complex a subject to expect any model to take into account many of its aspects – in this way models may become either simplistic or too deterministic, which prevents design exploration. Hewett and Burke (2010, p. 146) argue that instead of homogeneous parametric models, projects of significant architectural complexity require multiple and loosely connected ecologies of parametric systems to be relevant in terms of design

control and in terms of relationships to larger social, environmental and political contexts. Students' comments throughout the studio discussed in this paper echoed these viewpoints. One student team commented that "the translation between human thought and computer language is not very direct and requires a lot of effort". Students in all teams found some aspects of their designs easier to approach parametrically than others: When faced with this decision, they simply used the approach they thought was best suited to the task, which led to a unique and pragmatic combination of methods and viewpoints in each design team. Parametric designing was used in particular for façade patterns and automated function layouts within large volumes of space. In some cases, parametric models were apparently established too early, and the parametric logic became too limiting for the architectural design required. In several intermediate design critiques, students were asked by teachers and critics to "break" overly consistent parametric models in which generated variety was seen as arbitrary or meaningless. Figure 3 (left) illustrates an example in which a constraining parametric model needed to be "broken", adapted, modified and integrated with other design approaches to achieve the architectural ideas aimed for as illustrated by students' sketches (Figure 3, right). Departing from the constraints of the parametric model in these cases allowed for an architecturally more appropriate understanding of variety.



Figure 3. Overly constraining parametric model (left) compared to students' sketches (right).

Since these comments came from critics who have long-term practice in parametric modelling, this observation may call for a more differentiated understanding of parametric generation of variety in the architectural design studio. Where in previous educational studies, the teaching of parametric modelling and programming were typically the primary aims, the studio discussed here focused on architectural design. Parametric tools and design approaches were offered and taught but not required exclusively. This gave students the flexibility and opportunity to openly reflect and comment on the challenges of achieving the desired architectural quality by exclusively using parametric modelling. Critical feedback was encouraged and did not reflect badly on students' grades. Educational approaches in teaching parametric designing as

part of architectural design studios may require more research and discussion regarding how parametric designing can be integrated with other ways of working and thinking.

5. How was students' work evaluated by teachers and critics?

The analysis of detailed transcripts of design critiques demonstrated that teachers and critics evaluated students' work and progress in two broad categories: the mastery and application of parametric tools on the one hand, and the quality of architectural design proposals on the other hand. In design critiques, critics and teachers consistently commented on either one or the other of these aspects when giving students feedback. When questioning students about their parametric models, teachers and critics typically expected students to provide rational explanations and appreciated ways of reasoning that described the purposeful use of parametric model construction. When commenting on architectural qualities however, critics and teachers tended to employ and expect a more qualitative or emotional language describing spaces and social context. Based on these observations, it seems that in the case of this studio, parametrically designed proposals were *explained* through reference to parametric models and their rationale. Parametrically designed proposals were however *judged* based on more broad architectural qualities, which did not necessarily take into account parametric models or rational reasoning. Once parametric designing is employed in an architectural design studio, the main criterion for evaluating student work is not whether students successfully learned techniques, as it may be the case in technical courses, but the overall quality of the design proposals (Iordanova 2007, p. 689). The analysis of successive design critique transcripts in the case of the studio discussed here indicates that students gradually learned to report a "parametric narrative" to satisfy teachers' and critics' expectations, while pursuing architectural aims through design approaches that often modified and abandoned exclusively parametric modelling. Student groups who initially commented critically on their experiences with parametric modelling later reported 'success stories' in final questionnaires, which may be due to the perceived pressure to present successful parametric design accounts. One aspect of parametric designing thus seems to be the development of parametric narratives to fit criteria and values to associated with parametric design proposals, as emphasized by Schumacher's 'Parametricist Manifesto'.

6. How did the parametric design approach work for Chinese students?

While any attempt at characterizing or explaining the values of any design

tradition explicitly is bound to be overly generalized and inadequate, I still would like to address this aspect since it has not been discussed within the field of CAAD research and education previously. The relevance of this aspect may elude readers raised and educated within the Western tradition: Cultural values tend to be invisible to those who share them and tend to become obvious mainly when they are challenged for some reason. The Chinese cultural context can be described as a “high context” culture according to Hall’s (1976) framework, where much that is made explicit in Western cultures tends to remain implicit in communication. This aspect has been discussed in fields as diverse as management and web design, but has not yet drawn attention in digital design research. In the context of digitally supported designing, the parametric approach can be seen as a challenge to Chinese traditional design education, where evaluation of architectural work often depends on implicit emotional or pragmatic appreciation of the proposed form, in which evaluation criteria are rarely made explicit.

Kolarevic (2003, p. 27) states that with parametric designing, “architects are designing not the specific shape of the building but a set of principles encoded as a sequence of parametric equations by which specific instances of the design can be generated and varied in time as needed”. This characterization shows the important role of explicit logic and rational reasoning in parametric designing. Many students commented on this aspect: “Western thinking seems more logical and more direct while Eastern design thinking seems more emotional and more indirect. Different ways of thinking may yield different results.”, “This way of working seems more technical and can help us achieve several aspects of work beyond our previous scope”, “When designing based on the parametric design approach, we had to find a way to make our idea explicit in an abstract architectural language. It’s kind of bitter sweet”. Deprived of a sensual or immediately form-based approach to architectural designing, many students initially struggled to see designing in terms of numbers and parameters. Students also commented that they disliked “making everything technical”, and that they found it difficult to think of design in terms of “control”.

With the introduction of parametric designing, students’ and critics’ attention seemed to shift towards issues of rationally describing sculptural form and away from the human-centred consideration of spatial experiences. Students were proud of the kind of shapes they could generate through parametric models, and the moments of surprise when seeing the outcomes generated through parametric variations: “We initially created a logic of related parameters according to our design ideas and aims, and implemented this logic in a Grasshopper parametric model. Parametric variations mostly concerned the

geometric operations of revolving, twisting, connecting and separating”, “We found parametric software useful to form a great variety of beautiful shapes which we think cannot be done by conventional tools alone”. The requirement to make design decisions explicit was experienced by students in various ways. Some students commented that their way of thinking was widened by the experience. Students appreciated most the experience of working parametrically in design teams, since making design ideas explicit in terms of relationships of parameters and numbers helped the groups to negotiate shared understandings.

7. Conclusions

This study presents the outcomes of a qualitative analysis of a single case study project in which the process of introducing parametric designing to students new to the subject was examined in an architectural studio setting. Results of the grounded analysis of field observations as summarized in the following are offered as points of departure for both educators as well as researchers employing or examining parametric designing as part of the design studio, in particular in Chinese or Asian contexts.

In students’ design processes, parametric models were developed and used only after a phase of idea development through diagrams, which allowed for easy transformation topological aspects. These diagrams were often based on existing diagram formats and fulfilled a similar role to the parametric model referents employed by Iordanova (2007). Parametrically generated variety seems to affect models mainly in terms of shape but does not allow much deviation from predefined topologies. Breaking or abandoning overly rigid topologies of parametric models and integrating these with other modelling approaches seems necessary to pursue design aims which further supports observations reported by Hewett and Burke (2010).

In intermittent and final design critiques, students’ work and progress was evaluated in two broad categories: the mastery and application of parametric tools on the one hand, and the quality of architectural design proposals on the other hand. While parametric modelling provides a context of justification and explanation, critics tended to evaluate parametric design proposals in terms of architectural quality, which resulted in two distinct categories of criteria. With teachers and critics expecting parametric design explanations, but evaluating based on more conventional architectural design criteria, parametric designing tends to become a framework of values and a narrative that glosses over students’ need to manually revise and modify parametric models to achieve the desired architectural aims.

In this studio, set in a Chinese cultural context and design tradition, working

with explicit design rationales and reasoning as required by parametric designing has presented a challenge: Parametric designing in this studio encouraged sculptural form variation but tended to discourage thinking in terms of spatial qualities. Participating students felt that parametric design proposals could achieve form variation but felt limited in their ability to express their architectural ideas. Students however commented positively on the usefulness of parametric designing in teamwork, where making ideas explicit helped to negotiate and communicate about design proposals in groups.

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THE HEADSPACE PROJECT

Computer-Assisted Fabrication as an Introduction to Digital Architectural Design

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Abstract. Written for architectural educators, this paper discusses whether digital fabrication can be usefully employed in early architectural education. The paper uses examples from a course that aims to introduce the fundamentals of digital architectural design to first-year students. To achieve this, the course integrates digital fabrication as the core element of the production workflow. Challenging but rewarding, early adoption of digital fabrication exposes students to the process- and material-based thinking of contemporary architecture at a time when they form lasting attitudes to designing.

Keywords. Architectural education; digital fabrication; digital architectural design; creativity; process-based designing; performance-based designing.

1. Introduction

Architectural education needs to respond to the rapidly increasing utilisation of computation in architectural design. Digital fabrication in particular is gradually gaining prominence as a fundamental shift in design development and construction (e.g., cf. Kieran and Timberlake, 2004; Addington and Schodek, 2005; Kolarevic, 2003; Sass and Oxman, 2006). Being able to fulfil “informed *manufacturing* potentialities [becomes] a principal strategy in realising innovative contemporary architectural design intentions” (Kolarevic and Klinger, 2008, p. 7). The contemporary condition of rapid change and intense experimentation poses a difficult challenge for architectural education because architecture schools have to introduce the new knowledge in

parallel with its emergence. Major transitions are difficult for educational institutions that have established curricula, ways of thinking about architecture and employees educated within previous paradigms. It is easier to introduce experimental techniques in smaller graduate courses that attract experienced students already interested in digital creativity. Indeed, the pioneering of new approaches to date has largely occurred in such courses, often lead by influential practitioners (Oxman, 2008, p. 100). This is understandable given that undergraduate courses commonly have larger class sizes and involve students that lack specialist preparation or proven commitment. Utilisation of digital fabrication in foundation courses is particularly unusual. The closest example we could locate is Özkar's (2007) description of a first-year course that introduces learning by making in the context of design computation. Motivated by similar concerns, this implementation still seeks to provide an analytical foundation for future experimentation at the graduate level and does not engage computation for first-year project work, preferring to introduce relevant methods with analogue means. However successful, small studios utilising digital fabrication at the graduate level cannot reach all students or institute an early acquisition of relevant mental and practical habits. When Bauhaus or VHUTEMAS presided over similarly major shifts in design education, the acculturation to the new ways of thinking in the foundational courses was deemed essential (Khan-Magomedov, 2000; Wingler et al, 1969). Engaging with this challenge, this paper discusses a foundation course that introduces the emerging principles of digital architectural design through digital fabrication.

Early design studios

The design studio is an essential device of architectural education. It supports experimental exploration of concepts, representations, materials and processes, introducing students to the designerly ways of thinking. Its usefulness as a place of learning through making is confirmed by the artisan traditions, Dewey's (1916) philosophy of education, Bauhaus's *Vorkurs* and recent research (Temple, 2007).

The role of the first-year studio is particularly important. It helps students to form initial ideas about design and architecture, to establish the foundations of their personal creative practice or – as legitimately – to convince them not to specialise in architecture. These first encounters with designing introduce students to wicked problems and the ways to tackle them. Most new architecture students need to abandon their preconceptions about designing (for a parallel discussion, see Temple, 2009) because their understandings of creativity are often naïve and their knowledge of useful architectural precedents – mini-

mal. Moreover, design studio work typically requires significant transformations in learning behaviour, away from habits formed during pre-architectural education. Such transformations can be challenging and uncomfortable. To minimise their re-occurrence, it is important to initiate students into creative processes able to provide an enduring foundation for their learning and practice.

Digital design thinking

Discussing the challenges for architectural education in his work on design pedagogy, Oxman (2008) persuasively argues that contemporary design teaching needs to be founded on new digital design thinking rather than on templates typical for paper-based workflows. Today's computational capabilities introduce associative and performance-based processes that were not available in the pre-digital era. These new methods change the conventional relationships between such fundamental categories as ideation and making or form and material. Reflecting the new capabilities afforded by computing, recent architectural theory moved away from once dominant notions of formal knowledge, typology and representation to new concepts that prioritize dynamic generation in response to performance criteria and the linking of design development to the affordances of material systems (e.g., see Kipnis, 1993; Eisenman, 1999; Kwinter, 2001; Kwinter, 2008; Lynn, 1999). The need for change can be even greater in foundation courses that typically focus on explorations of shape, colour, rhythm, light and idiosyncratic experimentations with materials (Boucharenc, 2006) rather than on issues of performance, generation and emergence. The new emphasis on processes and materiality requires new vocabulary, new domain knowledge, new practical skills and – consequently – new approaches to teaching.

2. Structure of the course

The paper illustrates its discussion with examples drawn from one course, a constituent of a Bachelor of Environments program at The University of Melbourne. This course, entitled Virtual Environments, is intended as an introduction to the use of representation in architecture, landscape architecture, urban design and other allied disciplines. The course is structured around a practical project – called HEADSPACE – that necessitates learning about design precedents, encourages understanding of digital architectural design theory and convinces students to develop essential skills through practice. The HEADSPACE project asks students to design and build geometrically complex sculptures that can be made from paper and worn on the head (details are

available on request, for more, see: <http://vimeo.com/13719923>).



Figure 1. A headpiece design by Laura Ng; semester 1, 2010.

The course consists of four modules. In Module I (*Engender*), students use drawings and physical scale models to develop three-dimensional forms from the analyses of dynamic processes. In Module II (*Digitize & Elaborate*), students use orthographic projections, contouring techniques and/or point clouds to describe their models and convert them into three-dimensional computational representations. These representations are then modified and extended with digital modelling techniques. In Module III (*Fabricate*), students use computer software to unfold their models into two-dimensional components that can be cut out of paper. These components are then used to manufacture self-supporting paper structures, manually or with automated cutting machines. In Module IV (*Reflect & Report*), students produce documents describing their projects. These documents include justifications of design logic, evidence of analyses and precedent studies, precise geometric descriptions, how-to manuals and depictions of headpieces in context.

The course is run in challenging conditions. An iteration of the course can attract up to 400 students specialising in a variety of disciplines within and outside of design. For many, this is the first course of their introductory year at a university. The course lasts 12 weeks with one 50-minute lecture and one 2-hour workshop per week. Students attend lectures together and are subdivided into groups of 16 for the workshops. Each group has a tutor who meets the students during these workshops. The course is directed by a coordinator with the help of a senior tutor. Due to pragmatic constraints, the students are not provided with permanent studio space or dedicated computers. All software used in the course is freeware: GIMP, OpenOffice and SketchUp.

Previous versions of this course – coordinated by a different team – involved quasi-architectural project content (such as kiosks) and formal exercises (such as the task to represent a set of geometric shapes in orthogonal projections). Motivated by the ambition to teach representation in relationship

to the principles of digital architectural design, two semesters ago Stanislav Roudavski (with the help of John Bleaney, the senior tutor at the time) restructured the course to incorporate digital fabrication as its core technique. We adjudged that the building-scale briefs were a distraction for the new students who lacked previous design education. Predictably, their design proposals were uncritical copies of bland (or kitsch) commercial architecture. The complexity of architectural problems undermined students' ability to focus on heuristic, conditional and iterative development. In a course with the institutional remit to teach representation, there was no time to teach design history. Another solution had to be found. By replacing a series of small quasi-architectural projects with one comparatively abstract theme – the headpiece – we were able to free resources that allowed us to accommodate a challenging conceptual change and move from conventional experimentation with different design media to an exploration of digital architectural design with computer-enabled fabrication at its core. As a result, we were able to give students an opportunity to produce completed objects rather than tentative descriptions of proposals, such as drawings or physical scale models. We also asked students to cope with unfamiliar and unusual processed-based themes that discouraged uncritical adoption of existing design solutions or unthinking importation of conventional building types. To encourage emotional investment and make students feel greater responsibility for their projects we organised for the designs to be demonstrated in a prominent public event during a specially staged “fashion parade”. For young people whose creative personality is still in formation and who – many as teenagers – are particularly conscious of their public image, such public exposure can be highly embarrassing or highly rewarding. A public event at the end of the course caps a prolonged development process with a distinct and picturesque resolution reframing a potentially dry project as a socially meaningful and emotive encounter.

3. Learning outcomes

The focus on digital fabrication allowed a move away from outmoded emphasis (cf. Oxman, 2008, p. 106) on typologies, formal representations, visual precedents and arbitrary ideas. Instead, the structure of the course prioritises gradual, iterative development that searches for outcomes by exposing initial concepts to different media, techniques, contingencies and materials.

In addition to emphasizing these new concepts, this digital fabrication ascribes new meaning to the traditional tools of architectural ideation and development, including descriptive geometry, paper sketching, collaging and physical modelling. Working with these media within the framework of digital architectural design, students become accustomed to transferring design

content into different representational forms and learning their comparative characteristics. Interpreted “as design thinking through iterative stages of visual formal discovery”, sketching in paper (or in clay) can be justifiably seen as “the antithesis of the digital ‘matter and material’ approach.” (Oxman, 2008, p. 110) However, these techniques do not have to be bound by such a narrow conceptualisation. Integrated into the process underpinned by digital fabrication, they can instead be interpreted as devices that aid understanding, analysis and discovery. Indeed, as has already been argued (Garvey, 1997), traditional techniques, for example those borrowed from fine art, can enhance and guide digital experimentation. To illustrate, in the Virtual Environments course, students were asked to base their designs on an existing dynamic event, for example that of ink dissolving in water, plant extending towards light, a match bursting into flame, a sand dune pushed by the wind or a stalagmite rising from a floor. Having made a reasoned selection, they had to utilise several forms of representation for the analysis of the chosen phenomenon. This analysis could be conducted through a variety of sampling techniques ranging from a frame-by-frame review of a video sequence to the staging of a practical sedimentation process.

Forms possible via computer-assisted fabrication are unconventional and directly refer to the current state-of-the-art experimentation in architecture. Exposure to such forms and associated methods encourages students to question their preconceptions of architectural designing and its products. Instead of continuing with a typical romantic image of a designer as an idiosyncratic creator, the students experiment with process-based approaches. Because relevant theory and precedents are less obvious to newcomers, the students cannot rely on existing knowledge and have to engage in independent search for the relevant conceptual context and the existing communities of practice. In our experience, this need has the capability to inspire the students and tutors alike. It can also leave behind weaker students who are unwilling to do independent research. Making them understand and assimilate deeper theoretical implications remains our primary challenge.

Introduction of fabrication allows students to develop ideas in response to the contingencies of making, closer to the way design happens in practice and in extension to the more typical approaches to architectural education that support students through ideation but frequently do not provide opportunities to engage with production. (Lara et al, 2009)

The digital fabrication workflow requires coordination between different media and skill sets. By focusing on a holistic challenge of fabricating a complex form, this approach provides a context that demonstrates how multiple types of media satisfy different pragmatic needs. Working on the project, stu-

dents acquire skills in physical modelling, sketching, drawing, photographing, digitization, three-dimensional modelling, unfolding, fabrication, writing and desktop publishing.

Engaging with such challenges in the context of digital fabrication is particularly useful because it results in easy-to-perceive successes and failures. If the final paper headpiece does not assemble, it is clear that a geometric mistake has been made. As a result, “[w]orkmanship becomes evident as a category of design decision-making, not simply as a by-product or something that might be spoken of at a designer’s whim.” (Temple, 2009, p. 220)

The introduction of conceptually and technically challenging content is never without difficulties. We could not supply computers or industry-standard software to all of our students. However, this was overcome with the use of free-to-use software and students’ laptops. Such software brings limitations but also teaches students to cope with difficulties and acculturates them into online communities that are vital for digital creativity. Similarly, it is still a challenge to find tutors able to teach digital fabrication and – especially – its conceptual implications. This can be partially offset by carefully prepared course content and should improve with time as ideas and knowledge propagate through the pedagogic community. Another difficulty was brought about by our choice of the headpiece as a design theme. Some students struggled to see the similarities between these abstract structures and the larger scale architectural projects despite our efforts to highlight such similarities in lectures. If history and theory on one hand and mathematics and geometry on the other were supporting the theoretical discussions and practical work on digital architectural design, the conceptual implications would be more obvious. As it was, students struggled with the idea of a process as a design theme but many have overcome this challenge successfully, sometimes in truly innovative ways. Finally, complex fabrication workflows requiring multiple versions and frequent remaking tend to consume a lot of time. Sometimes the best students are left dissatisfied because their proposals cannot be faithfully fabricated within a tight schedule. However, such constraints mimic those typical in design practice and produce learning benefits even when the resulting objects are oversimplified or poorly built. As the next section will demonstrate, these difficulties did not stop our students from appreciating the important aspects of the course, producing spectacular results and learning a great deal.

Qualitative educational benefits of this approach are hard to measure. Instead, we prefer to evaluate the impacts of the course through the students’ feedback discussed below and appraisals offered by academic and professional peers. The latter included a congratulatory reception of the local exhibitions by academics and others, coverage in press, exposure in more than a dozen

international design blogs and admissions into the programs of two international films festivals on art and design (for more, see: <http://www.facebook.com/pages/Headspace-projects/152613348100201>). This response confirms that the course provided a large group of first-years students an unusual opportunity to produce publicly acclaimed design work; an outcome that we hope can be classed as a benefit.

4. Student response

Student response in a large and complex course operating under multiple and contradictory constraints is also difficult to evaluate. In order to understand it better, we conducted regular formal surveys using anonymous questionnaires that included multiple-choice questions for the collection of quantitative data, specific questions for qualitative feedback and fields for unstructured comments. We also instituted a mechanism for student representation. Each tutorial group of about 16 selected a representative. The academic staff met these representatives at several occasions that allowed discussion of specific issues and opportunistic feedback. Data from the questionnaires, records of the representatives' meeting and the discussions on the online forums have all contributed to the analysis of the student's response and the learning outcomes.

One theme that emerges from this feedback is that students find the approach based on digital fabrication simultaneously more challenging and more rewarding. The difficulty seems to dissuade the ones who are less committed or lack the aptitude: in the second iteration the course size dropped by 30% in the first two weeks. Given other circumstances the discussion of which is beyond the scope of this paper, the ability to select more suitable students in this way is a reasonable outcome.

Many students agreed that the project meaningfully tied together a number of subfields, as one student noted: "excellent idea to get through the entire process from design to fabrication – very satisfying."

One student reported that the subject "required more time than the others to achieve high marks" and yet that he/she (the response was anonymous) "felt the most motivated to succeed in this subject than any other." This comment expresses a common sentiment, especially in the second iteration of the course. At the same time some students felt that the workload was excessive. It is revealing that the number of students that felt demotivated by the workload has dropped dramatically in the second iteration of the course. This is despite the fact that this generation of students had to cope with more challenging project requirements and that the total amount of work had not changed significantly. We reason that perceptions changed so dramatically because in the second iteration we were able to refer to the examples of student work gen-

erated earlier. This has helped to illustrate the expectations by demonstrating different types of geometry, expected levels of craftsmanship, efficient types of workflows and so on. A semester-one common comment stating that the “beginning of the subject was too vague, perhaps an example of what we were aiming for could have been shown early in the semester” has largely disappeared in the second iteration of the course.

Students’ comments also confirm that the fabrication of a completed object is a useful and satisfying experience, or as one student put it: “seeing your final finished model was rewarding as it was a challenge to create.”

Finally, our decision to present the resulting design in a large public event also worked to motivate and reward the digital fabrication work. The “fashion parade” helped to put individual achievements into perspective by exposing them side by side with other, conceptually or qualitatively differing headpieces. “For the amount of work I did on this subject I was a bit disappointed at the marks I received. However comparing my work to others on the parade night I understood that my final fabricated design was at a lower standard; and I know I am still learning so I am happy with the marks I received.”

5. Conclusion

As Özkar (2007, p. 100) states, “how the notion of making in the studio prevails in the age of technology remains to be investigated”. Seeking to fill this gap, our paper suggests that design projects structured around digital fabrication can be successfully sustained in the context of early architectural education and result in an integrated learning of theory, techniques and creative practices pertaining to the emerging paradigm of digital architectural design. Unusual at the time of writing, such integration in the context of a foundation course is a pedagogical innovation. The suggested approach is characterised by the following important choices: 1) the design project at the core of the course is simple, abstract and full scale; 2) the course allows the student to follow the design process from inception to completion, focusing on processes and gradual iterative development; and 3) the course concludes with a dramatic public event that brings the students together in an emotionally challenging but rewarding setting. The pedagogy discussed in this paper is significant because it demonstrates how architectural education can begin incorporating the influences of computation. Teaching digital fabrication at the very beginning of architectural education transforms students’ understanding of design and moulds them as creators. If their understandings become aligned with the state of the art from the very beginning, they gain a lasting foundation from which to plan their education and careers. These effects should be studied better and this paper invites further experimentation. We would also be grateful for feed-

back or information on other similar courses run elsewhere, if any.

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THE SOCIAL NETWORK VIRTUAL DESIGN STUDIO

Integrated design learning using blended learning environments

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Abstract. Online communications, multimedia, mobile computing and face-to-face learning create blended learning environments to which some Virtual Design Studios (VDS) have reacted to. Social Networks (SN), as instruments for communication, have provided a potentially fruitful operative base for VDS. These technologies transfer communication, leadership, democratic interaction, teamwork, social engagement and responsibility away from the design tutors to the participants. The implementation of Social Network VDS (SNVDS) moved the VDS beyond its conventional realm and enabled students to develop architectural design that is embedded into a community of learners and expertise both online and offline. Problem-based learning (PBL) becomes an iterative and reflexive process facilitating deep learning. The paper discusses details of the SNVDS, its pedagogical implications to PBL, and presents how the SNVDS is successful in enabling architectural students to collaborate and communicate design proposals that integrate a variety of skills, deep learning, knowledge and construction with a rich learning experience.

Keywords. VDS; social networking; social learning; problem-based learning; PBL; Web2.0.

1. Introduction

Since the early 1990's the Virtual Design Studio (VDS) established itself as a well-functioning learning environment that allows students in various locations to engage synchronously and asynchronously in design learning. VDS have facilitated collaboration across international boundaries and helped re-

define the social and cultural contexts of the design studio, whilst providing learning opportunities for students within the context of the internationalization of architecture. In the recent past new technologies allow the VDS to evolve into new directions – some of which addressing shortcomings of the past. Web 2.0 technologies, digital native users and universities' investments in e-learning and content management systems have triggered a radical shift of how architectural design is taught by teachers and produced by students (Ham, 2010).

The VDS established virtuality as acting while physically distant or as acting by employing digital tools (Maher et al, 2000). Virtual Environments (VE) were established by the choice of design (Achten, 2001), way of communication (Schmitt, 1997) or digital tools (Kurmann, 1995). Later the VDS developed into real immersion within a VE, the medium for design interaction being the VE Design Studio (VeDS) (Schnabel, 2002). With the advent of Web 2.0 technologies, it became apparent that the next logical step to develop the VDS was collaboration within a social learning environment (Schnabel and Howe, 2009). Ease of communication, leadership opportunity, democratic interaction, teamwork, and the sense of community are some of the improved aspects that are offered by Social Networks (SN) (Owen et al, 2006). Mitchell (1995) also refers to the need for an ongoing 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 is presented here.

2. SNVDS Case Study: A third year architectural design studio

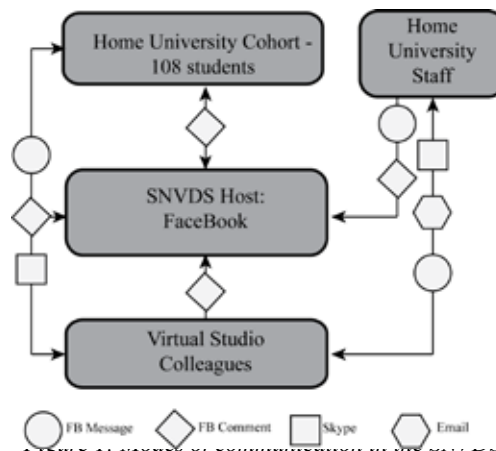
The architectural design studio presented here is a core third year design unit in the Bachelor programme at Deakin University. The studio operates in on-campus mode with an enrolment of 110 students. The unit is the capstone in the undergraduate degree and is conceived as the unit wherein students demonstrate their prerequisite skills for entry into the Masters Degree programme.

The 'Architecture 3b'-SNVDS comprised two projects. Firstly, a five week project titled "Rock and Roll Architecture", whereby students designed an inner-city music studio and rehearsal space. This project was weighted 40% of course marks, and required students to complete a five minute video presentation of their design, utilising *YouTube*TM for project submission. The second project, "Future City Hong Kong", project was a seven week project based on the design of a pencil tower in the district of Tsim Sha Tsui, Hong Kong, and

was weighted 60% of unit marks. The 'Future City Hong Kong' project will form the focus of this paper; however refer to Ham (2010) for research relating to Project 1.

The project was framed around an international competition format, with the brief based on a Hong Kong developer demolishing the existing building in Tsim Sha Tsui for a fifteen storey building. 'The client is most interested in maximising rental return on the property. In achieving this, they wish to market the building as a 'Low Energy Mixed Use Development' and intend to capitalise on this prime point of difference' (unit guide, 2010). The brief required a ground floor flagship store, four levels of mixed-use retail, four levels of accommodation, three levels of restaurant and a top floor nightclub, based on a footprint of approximately 9x11m. The site is located within a high dense commercial environment, but is also opposite a large, open landscaped park (Kowloon Park).

Deakin University requires all units to be hosted on the centralised Learning Management System (LMS), Deakin Studies Online (DSO), which operate on *FirstClass Technology*TM. Engagement in DSO for this unit was the minimal required by University policy, and was limited to the posting of a Unit Guide and a repository for digital resources to support project work. The design of DSO disallowed engagement of people outside of fee-paying students and Deakin staff who have been given password-controlled access. Academics and practitioners outside of Deakin are denied access to unit materials completely. DSO was found to 'effectively reinforcing the creation of dis-integrated knowledge silos' (Ham, 2010), thus limiting the potential of the design studio programme.



The *FaceBook*TM (FB) -group set up by the unit chair was the principal enabler of the SNVDS. Students cohort in the FB group had full read and write access to specific functions of FB: 'wall', 'discussions' 'photos' and 'videos' and 'read-only' access to 'events' and 'info'. The unit chair was the main facilitator of posting of events and discussion entries relating to the unit and projects (Figure 1).

*Skype*TM was used to facilitate video and voice communication between students and virtual studio colleagues. Video-based lectures and seminars with student groups in lecture theatres by Hong Kong-based colleagues provided the dissemination of facts about Hong Kong's climate, culture, as well as important information relating to the site that was inaccessible from the Home University. Impromptu Skype sessions occurred within the design studio to allow students formative and informal feedback from virtual studio colleagues on individual design works (Figure 2). In the final reviews, video-based feedback was provided to students in a hybrid virtual-physical review session, with virtual studio colleagues providing a real presence within the review. In Summary the studio was enriched and expanded with a blended learning environment that had at its core a social environment and multiple means of communication and engagement.



Figure 2: Skype-based virtual feedback session in the design studio

3. SNVDS as a framework for problem-based learning

Most approaches to problem-based learning (PBL) are sequential following the conventional method of Albanese and Mitchell's (1993) seven steps

model. Yet, this linear format is limiting and imposes a structure that does not fit with an iterative and reflexive processes facilitating deep learning. Flexible interplay between the seven steps improve the social engagement of students of the 'Net-generation' (Oblinger and Oblinger, 2005), especially where social networking sites are used to replace or augment the PBL tutorial or studio sessions.

Technologies of Web 2.0, by embracing problem-based learning, have utilised blended learning formats, where face-to-face contact is supported by instructive resources such as *WebCT*TM, *Blackboard*TM, web-blogs or static websites. However, the effectiveness of these platforms for online learning has been limited by typical Web 1.0 approaches to learning (Oblinger and Oblinger, 2005). The internet, when employed as a filing cabinet for resources or post-box for messages is too unwieldy to generate the experience of flow that motivates deep learning (Craig, Graesser, Sullins, and Holson, 2004). Further impeding the effective use of Web 2.0 technologies has been design of learning experiences by teachers from the 'Baby-boomer' or 'Gen-X generations', who do not think or learn in the same way as their students (McNeely, 2005). It is thus important that PBL flexibly encompasses the thinking and learning styles of both teachers and students. Existing PBL structures provide scaffolding for problem definition and access to resources and learning objective development, which are transferable to online platforms. Subsequently, for successful learning in the present online environments, educators must now constructively address additional issues: motivation for interaction (Craig et al, 2004), processes for socialisation (Dede, 2005) and moderation for exchanging information (Salmon, 2000).

In a non-linear modification of Salmon's (2000) model of e-learning, the learning experience is the context surrounding the process of knowledge construction, which is a interlinking of concepts and actions spanning two broad areas of endeavour: educational/technological scaffolding and social interactivity (Figure 3). Access to resources and problem development inform the scaffolding while social interaction and information exchange are facilitated by the potential for interactivity of the learning tasks. All components of the process are interlinked. Since all members of the learning community (teachers, students and other relevant stakeholders) contribute to knowledge construction, they are not represented as disparate entities in this model. The traditional steps of PBL are subsumed in the educational scaffolding but are modified to suit the online technology.

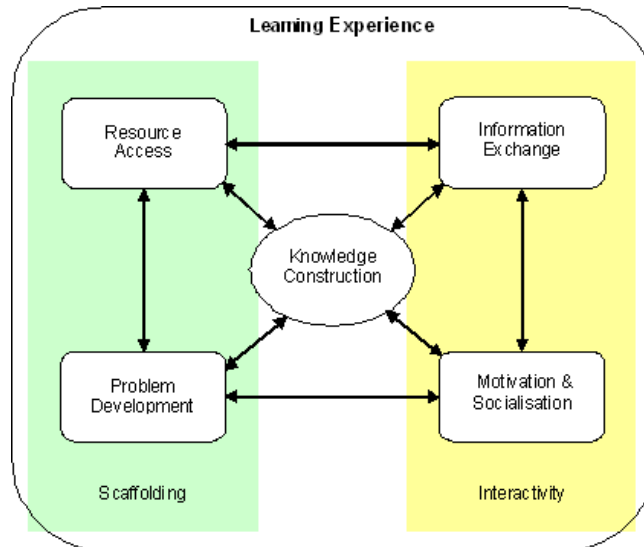


Figure 3: A social interaction model of e-learning by Howe and Schnabel (2011)

3.1. SCAFFOLDING: TECHNOLOGY AND RESOURCE ACCESS

Online learning strategies emerged in Architectural education in the last two decades (Kvan, 2001; Achten, 2001; Schmitt, 1997; Kurmann, 1995; Maher, Simoff and Cicognani, 2000; Schnabel, 2002) and recently into a more social learning environment (Ham and Dawson, 2004). SN impact on the quality of engagement and learning outcomes (Schnabel and Howe, 2009) through ease of communication, leadership opportunity, teamwork, and a sense of community (Owen, Grant, Sayers and Facer, 2006). Finally, the finding that design productivity may be better supported by remote settings than co-located ones was raised by Kvan and Gao (2006).

Students were surveyed at the beginning of the trimester on their use of SN. Over 90% of students already use such platforms. The FB site was made accessible besides to the students and tutors of the course to anyone who was interested in the topic of the studio. Students undertook research relating to their design task and target audience and posted this information as a shared resource for use and discussion by all participants. Significant opportunities were provided for student-staff interaction online, mostly outside studio hours, and contact using other media was also possible (mobile phone, video-chat, etc.). This is a particularly important issue in the context of diminishing resources within the school for seasonal staffing and a staff: student ratio

of 1:27. Staff, experts and peers were commenting and posting additional resources to further enlarge the students learning.

3.2. INTERACTIVITY: MOTIVATION AND SOCIALISATION

Motivation and socialisation were facilitated through site personalisation of the SN website, opportunity for development of flow and diverse learning activities. Respecting personal characters in the learning experience of the students the SN facilitated flow (Csikszentmihalyi, 1996). Flow is an important component of creative knowledge environments and has been found to facilitate content acquisition, teamwork and positive affect towards subject mastery (Beylefeld and Struwig, 2007). This positive affective experience in turn increases team effort and spontaneous communication. Huang (2003) argued that motivation is enhanced or maintained by flow, achieved when the site is pleasurable as well as functional. The studio FB-site included a 'wall'-discussions, videos, chat, photos and RSS-feeds enhancing motivation because they enable hedonic experiences.

3.3. INFORMATION EXCHANGE

While social interaction is necessary for information exchange it may not be sufficient; the learning activities have to be varied, challenging and meaningful. Information exchange in the program occurred in multiple areas of interaction: with peers, resources, teachers, other stakeholders and the community. Not only does blended learning involve integration of different media for information exchange, it also involves amalgamation of the contributions of all members of the learning community, a process for developing collective intelligence (Levy, 1997). SN provides a mechanism for presenting collective information for individual use as well as aggregating individual insights into a collective decision (Surowiecki, 2005). The PBL experience was situated within the professional realm and the wider online communities, thus providing a transformative environment for blended learning.

3.4. KNOWLEDGE CONSTRUCTION

Darling-Hammond et al (2008) found that deep learning is enhanced when students apply classroom-gathered knowledge to real-world problems, a process requiring sustained engagement and collaboration. Active learning practices have an impact on student performance greater than any other variable, including student background and prior achievement. The current PBL experience addressed three criteria for authentic learning and teaching developed by Newmann and Wehlage (1993): construction of meaning and pro-

duction of knowledge, disciplined enquiry to construct meaning and production of discourse, products and performances that have value beyond school. To research the problem required higher order thinking combining knowledge from design, culture and construction to generate a successful overall outcome. Students had to research local conditions, collect environmental and cultural data and develop a design concept, which integrated all architectural elements.

In construction of a design that fits the local requirements and contexts, social interaction intensified with peers, friends and other FB members. Because each member had to find out appropriate information via their SN environment, the students remained motivated and engaged with the PBL program; similar to findings of Schnabel (2002), a process analogous to a typical collaborative scenario in practice, where designers and specialists contribute to an overall scheme in sequential and parallel activities. The learning discussion involved social networking utilising both human resources and design technology, a convergence of social communication and technological environments. An important benefit of this convergence for facilitators is the opportunity to learn with and from the students. Students are often ahead of teachers in mastery of technology (McNeely, 2005). The loosening of the outdated hierarchical education system, reframing teachers as facilitators of social learning, provides the great opportunity for teachers to upgrade their own skills in the process of working with their students.

4. Conclusion

The SNVDS moved participants from sequestered autonomy into an enriching, deep learning experience in communication and design. It engaged both students and academic staff in learning about professionalism, communication, collaboration, and cultural engagement.

SN environments offer new opportunities for creative development of PBL because disciplinary, professional, institutional and national boundaries are more easily permeated. Social multi-nodal networking sites (*Ning*TM, *YouTube*TM, *Google Docs*TM, *Doodle*TM, *Facebook*TM, *Twitter*TM, Wiki's, or other mash-up multi-dimensional platforms) were meaningful integrated in learning activities enabling communication of learning goals, disseminating learning resources, creating knowledge and original ideas, providing feedback and aligning with assessment of learning outcomes. These media-rich platforms don't solve all problems educators and learner have; the constant change of technologies, interfaces, social trends and risk of failure are omnipresent and increase the flow-effect. It adds a certain weight and responsibility to the educator to facilitate the learning environments and recognise the dif-

ferent levels of expertise and experience of the learners. Yet these platforms allow learners to reframe their problems in such a way that these problems can be explored in learning activities, thus enriching the current praxis of PBL. They are effective at tapping into social capital; therefore the process facilitates students' self-directed learning in problem formulation and research and it becomes possible to embrace professional and interprofessional SN communities to achieve higher levels of collective intelligence. The challenge remains the same: to facilitate student learning. It is the way in which we engage each other in these activities that is evolving to match today's communication needs.

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THINKING THROUGH DIGITAL SIMULATION TASKS IN ARCHITECTURAL EDUCATION

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Abstract. This study reports the activities of 80 second year architecture students at Victoria University, Wellington, New Zealand for the duration of a single trimester. A central theme in this studio is the framing of day-lighting problems into a quantifiable investigation and then addressing these through the use of digital modelling and simulation tools. This study offers an insight to undergraduate architecture students' negotiation of digital design spaces and asks the question of how the knowledge of skill-based specialist tasks are extensible to core design studio. The mass education within a University environment of such specialist skill based techniques allows for an insight to the negotiation of quantitative and qualitative design criteria. The issue of learning skill based tasks at university level is a pertinent topic of study as the critique of such techniques is implicit to the holistic education of Architects but the level of this critique can vary greatly. This question also highlights the challenges faced to improving the design education approaches to computational thinking and applications.

Keywords. Design analysis; daylight simulation; education.

1. Introduction

Whilst daylight analyses have been previously applied to architectural applications mainly through heuristic methods¹, newer tools have made this area more accessible to design studios and CAD based environmental science courses. This paper reports the activities of an undergraduate design studio which aims to have daylighting as a central theme; where lighting comfort and quality become an integral part of design problem solving. The traditional studio environment and professional culture can create a separation between

disciplines; the design studio at the core and various specialised tasks, such as lighting or structural analysis as satellite events mainly to verify the feasibility of a design. Newer studio and teaching methods including descriptive analysis methods (Reinhart, 2006, 2009; Koutamanis, 2001) for environmental assessment have been applied in an attempt to overcome this obstacle and streamline students learning.

The undergraduate architecture degree contains several gate keeper core courses which require students to learn technical skills, develop understanding and to apply these to concurrent studio design papers. *Human Environmental Science*² is one such paper taught at Victoria University Wellington NZ (VUW) School of Architecture at the second year level. The theoretical aspirations for such courses can risk being at odds with the actual level of achievement and application of design aid tools within the studio environment. The reasons for this can range from programme scheduling, cross-integration of assignments, tutorial size, tutor availability and the delivery of skills training. Whatever the issues or reasons, an effort can be made to improve the status quo and to convey the course content in a way which is more stimulating and rewarding to students.

At a time when class sizes are generally on the increase, higher levels of environmental analysis and technical outputs are becoming the norm. One concern of the authors is the effectiveness of an iterative design methodology which utilises accurate *descriptive* environmental analysis for students to compare and refine solutions *and* the given design problem at the same time. Following from this, there is a concern as to the effectiveness of skill based training resources. This is because students may acquire the required technical skills to accurately assess environmental qualities but this in itself does not guarantee a grounded understanding or adequate motivation for more adventurous or 'creative' solution development.

2. Background

Two decades ago the VUW architectural education programme was structured into courses that separated 'design' and 'science'. The latter papers focused on simple facts and design examples, examined independently from studio design³. The structured teaching of CAAD was also a separate activity relegated to communication courses. Design decision frameworks and other design methods described by authors (Koutamanis, 1993; Gross, 1994) were intended to be developed in studio projects. The structure created a separation of technical competence by way of skills training and the 'core' design studio. Specific 'Integration' projects in studio required the students to synthesise this content.

In 1996, a radical restructuring of the architectural degree saw the Human Environment and Design courses amalgamated, which addressed this concern as well as other pressures. A set of pragmatic lectures shared with Building Science and Interior Architecture classes formed the theoretical core of a poetic set of design projects in the Architecture studio. In these projects students were asked to tackle design tasks where the light, acoustic or thermal qualities were the principal focus. The projects were constructed around architectural challenges (for example “*To develop a music chamber*”) using well-known architectural typologies found from an examination of precedent. The focus of the course was on the students’ documentation through their design presentations not only the *poetry* of their idea but the *calculated performance* that met these goals.

The increased influence of digital applications in the programme was such that by 2003 the whole studio was digital; 3D model based set of projects with digital output of drawings. For much of the decade 1998-2008, the course benefitted from an interest by the school in additional digital craft skills coaching in the second year of study. The restructuring at VUW which took effect in 2010 separated the content back to two courses and provided the framework for the current system of integrated courses. This structure is described in Figure 1.

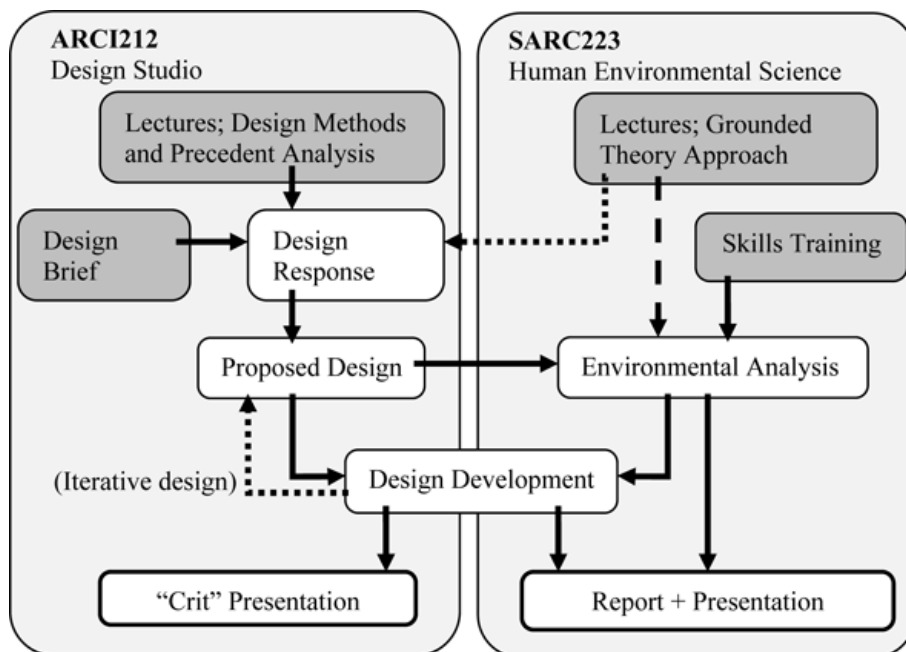


Figure 1. Diagram of current course structures

The current system could be characterised by an increasing focus on work processes and professional culture through pragmatic assignments as well as adaptation to updated methods of quantitative analysis. The goal is to take advantage of recent dramatic changes in the availability of CAAD and environmental analysis tools, as well as the ways in which studio culture operates. But there is still the problem of integration.

The following hurdles of detailed digital environmental assessment have been identified by the authors and others as impacting on both the level of craft and integration of the two courses:

- Special training required and time consuming to set up
- An accurate analysis requires specific environmental information
- A developed 3D model is generally required
- There can be a level of uncertainty of results and accuracy
- 'Integration' advice from studio tutors / consultants can be limited

These issues are typical for a range of existing environmental assessment methods. Some of the previous inadequacies highlighted (Paranandi, 2001; Ramasubramanian et al, 1999; Novitski, 1990; Hanna, 2001) revolve partially around technological availability and problematic user interfaces and processes which have to some degree been overcome. The issues are still relevant to the new course structure; but two in particular which could be addressed within the courses were that of training and model complexity. Issues of training were addressed as this is the first step in overcoming the creative limits of the applied tool. Model complexity was addressed as the recently available programs can manage complexity to the point where students are not limited by their ability to design and create complex forms.

The term *digital craft* is used to describe techniques which are paralleled in traditional craft processes and are used throughout the SARC223 paper and its precursors⁴. The hurdles students are asked to overcome are reduced by using the *best tool available*. The training hurdle is the most critical and allows for proficiency rather than the 'pressing of buttons' to achieve an end result. Like any tool, understanding the obtainable results and the limits of these results requires building a working knowledge and implementation skills. Once the resulting accuracy of calculated data is unambiguous, students are likely to approach a level of working proficiency. This allows for information to be applied in a thoughtful way to influence design decisions in both quantitative and qualitative ways.

3. Studio

The following description of the studio course objectives is quoted from the course and project descriptions:

A studio based paper with a series of architectural design projects applying evaluative and critical processes in architectural design, building environmental design methods, and designing with a client brief. Principles of people-environment relationships; satisfaction and comfort; heat, light, sound....

Initially you will develop your design, and build a 3D CAD model of it, which is to be taken into the accompanying assignments in SARC 223, for the purposes of Daylighting and Acoustic analysis.

The second part of the assignment will be to continue to develop your design, and your CAD model, and to integrate into it the information you have learnt from Construction, Structures, and Human Environmental Science, and present a final scheme that is a fully worked out completed scheme.

Daylight and sunlight illumination is one aspect in particular where integration or bridging the gap can occur. The reasons for this are clear when one considers the effectiveness of quotes from great architects such as Le Corbusier, Scarpa or Khan in stimulating the poetic aspirations of students to apply themselves to the assigned design problem. One key precedent for this assignment presented and analysed in lectures was that of the Jubilee Line extension in London by various architects including Norman Foster; in particular the “Fosterino” entrance of the Canary Warf Underground Station. Through precedent analysis the students realise that there are pragmatic aspects to achieving such poetic ends; hence there may be some motivation applying new techniques which reveal how these negotiations take place within a design process.

For this course the stance on digital tools was that the closer the language and medium of communicating the poetic and pragmatic aspirations of student designs the more likely that bridging of the gap can occur. This is because the formal visual abstractions and the analytical abstraction can now approach a near seamless transfer environment. The transfer of design intentions through iterative development of abstract models creates a situation where the barrier of translation is minimised and this can encourage ‘bridging of the gap’ to occur. Recent tools have been designed to allow for such translation operations.

4. Methods for technique learning

The approach to digital tools was applied in two specific ways not utilised in previous years; CAD teaching of Revit2010 in the studio paper and accurate lighting analysis in 3dsMax. CAD learning was aimed at reinforcing the 3D modelling skills for both design development and streamlining environmental assessment through export processes. For the first time in the recent history of the course the requirement of all students to learn a CAD package for studio design was enforced. In recent years this was *in effect* only mandatory for the environmental assessments. Implementing mandatory 3D digital modelling in the studio had the effect of reducing the distance between the architectural design model and the analytical model.

Reinhart's (2009) verification of a method of accurate lighting analysis in 3dsMax allowed for the first time in this course a close family of programs in which studio design, visual representation and accurate lighting analysis could take place.

A new approach was taken in the delivery of skills which addressed existing issues of demonstration and tutorial time limitations: on-demand tutorials via annotated YouTube videos. Previous experience highlighted the need for students to refer to 'on-screen' procedures rather than problematic and time consuming text based tutorials, whilst not relying on repeated demonstrations which would be necessary in large class sizes. The course structures limited the amount of time tutors could spend with students and so the emphasis on self-teaching and group teaching was increased.

Near the end of the studio design course specific questions were added to the regular University Training and Development Centre (UTDC) questionnaire to assess the perceived level of usefulness and integration of the skills taught through the online tutorials. Informal observations were also made through conversations with tutors and student representatives. These results and selected projects are described below.

5. Results and student examples

Informal observations regarding the students studio culture can be summarised as follows. Generally, the enforced requirement for CAAD training within the studio in conjunction with new on-demand online tutorials created a situation where individuals intensively trained themselves to a competent level within a few days of the start of the course. As time went on, the students with higher levels of confidence began assisting those who were lagging behind. The result was accelerated student-led group learning beyond expectations; at a level which could easily be described as a 'first' in this course and the

majority of students were able to set up accurate working lighting simulation models, albeit with simplified geometry, at an early stage.

Responses to the survey questions⁵ are summarised in Figure 2.

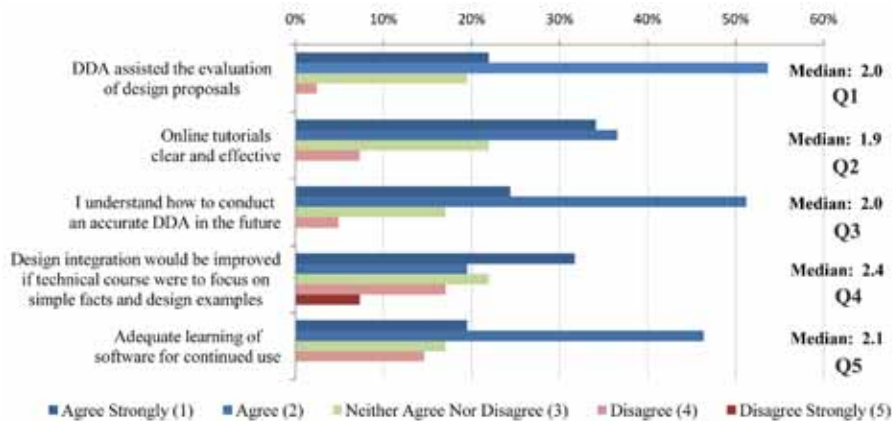


Figure 2. Survey responses (N=41) 'DDA' refers to Digital Daylight Analysis

These results reflected the students views that the analyses were useful (Q1), the online tutorials were helpful (Q2) and that assessment techniques would be used in the future (Q3+Q5). There was some disagreement between respondents regarding Q4; the majority of students would prefer some aspects of the 'old' system of assessment; but a proportion think that the structure introduced for the first time this year is working.

Two student examples are highlighted; accurate lighting analyses were applied to iterative design processes. Figure Figureure 3 shows modification of a dynamic roof canopy following lighting assessment which indicated high light levels and contrast causing glare. Figure Figureure 4 shows modification of a series of shaped perforations in the ground plane for a subterranean station following lighting assessment which indicated low light levels and inappropriate quality of light distribution. Both students analysed the light levels across a range of dates and times and responded to verifiably accurate simulation results through modifications which were in-line with response to brief and stated design intent.

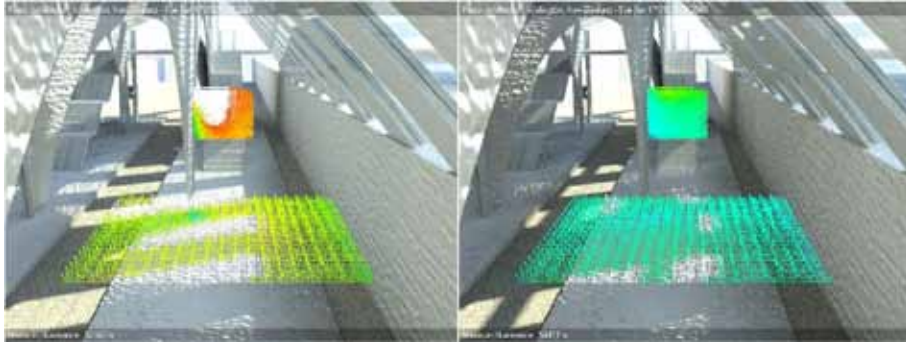


Fig 3; Monique Mackenzie covered transit station, showing illumination levels lighting analysis overlays; Iteration developed in response to contrast glare and roof fenestration pattern



Figure 4. Alex Sawicka-Ritchie subterranean transit station. 'Common-sense' design iteration confirmed through analysis of light quantities and visual quality of distribution.

Comments and feedback from students primarily focused on the relative accessibility of the relevant digital tools. There was a perceived isolation during the first two weeks as student activities focused on training – learning programs. When the tools were applied to a concrete design scenario, skill acquisition sped up considerably, as fellow students collaborated to improve the proficiency level for the majority. At this stage a shift occurred from following the calculation tasks given to understanding why they are performed. One analogy given was that it is like a blind person following the directions of someone else, and then being able to see.

6. Discussion and conclusions

The results presented in this paper show that the new system for integrating studio design and environmental assessment has had a positive effect in terms on student achievement and studio culture. In the past the inherent difficulties

of environmental analysis restricted the ability of students to sincerely apply quantitative analyses to iterative design processes of the traditional studio. These difficulties have not been completely overcome but the negative effects can be moderated through new digital platforms and technique based training methods. There are two ways in which the students in this new system can benefit from breaking with traditions of environmental assessment integration with design studio.

Firstly, newer methods in delivering skill based training have improved the relationship of environmental science and architectural design studio through streamlining support and encouraging group-led knowledge acquisition. The specific methodology of on-demand video tutorials introduced in a sequential manner assisted in raising the abilities and confidence of the studio group as a whole. There are still barriers to integration which appropriate technical training cannot overcome. Conducting digital daylight analyses will confront students with a large amount of information; how they use this material in reporting to tutors is of concern and may be the weak link in the chain. Also, tutors of the studio design paper have a lower skills base in the analytical techniques than is asked of the students; this is because most of these tutors from industry rely on the 'standard' set of architectural skills to adopt their role as design mentors. They are unfamiliar with the environmental assessment methods. Previous courses within the School have successfully used senior students as skills coaches to fill this gap rather than extensive up-skilling of studio tutors, but the dual role of design and daylight expert is a more difficult one to fill.

Secondly, the switch to descriptive analysis tools has largely removed the simplification and trivialisation which can occur with previous heuristic methods. There is also an added benefit to using a single platform which can accommodate design exploration and accurate digital analysis. The user interfaces of the newer tools allow for quick up-take of required skill set; and allow for assessment and iteration cycles in short time frames.

In conclusion, studio integration requires more than just good training of techniques, but there are tangible benefits to 'streamlining' the technical training process, as long as any new processes do not oversimplify the environmental science learning objectives or numerical skills.

Endnotes

1. Dean Hawkes has provided an early history of mainly heuristic methods (1970) and also updated observations (2008); Hannah (1996) also outlines methods.
2. See M Donn and J. Daish (1998) and Cuttle, C., Donn, M., and Baird, G. (1984) for the theoretical basis for the original 'Environmental Control Systems' course; now named 'Human environmental Science'.
3. The 'old' system from 2 to 3 decades ago: separate courses in design and Environ-

mental Control Systems; each with own 'design exercises': whole buildings, windows (daylight), fittings (electric light), energy flows (heating/cooling) etc.

4. Familiarising students with the workable capacities of a digital medium is essential but takes time and practice (McCullough, 1996).
5. The questions have been simplified for formatting reasons. The exact questions asked are as follows: (1) Lighting simulation analyses assisted the critical evaluation of design proposals in the core design studio projects. (2) I am confident that, in future design projects in the school and later in practice, I understand how to conduct an accurate lighting analysis. (3) I am confident that, in future design projects in the school and later in practice, I understand how to conduct an accurate lighting analysis. (4) Design integration in ARCI 212 would be significantly improved if the technical course SARC 223 were to focus on simple facts and design examples, examined in essays and exams. (5) I am confident that I have learned enough about the design analysis software like Ecotect that I can continue to practice on my own with other projects and develop and improve my skills on my own.

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IMPACT ANALYSIS OF DIGITAL-BASED ARCHITECTURE CURRICULUM ON STUDENTS' LEARNING

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Abstract. This paper reports the findings of assessing the impact of current digital-based architecture curriculum in architecture at KFUPM on students' learning primarily from students' perspectives. The paper addresses both generic and specific impacts of current digital-based architecture curriculum on students' learning. The specific impacts include: level of achieving better understanding of the architectural issues of buildings, and impacts of media qualities on understanding architecture. The paper introduces a performance improvement plan aimed at enhancing students' learning in the digital-based architecture curriculum and to accommodate the evolving nature of information technology applications in the building and construction industry.

Keywords. Digital architecture curriculum; students' learning; impact analysis; digital design education.

1. Introduction

Since the late 1980s architecture and architectural education have witnessed an important transformation with the introduction of computers and information technology (IT) in which they have become pervasive in all aspects of architectural practice and education. The pervasiveness of information technology in architectural education and practice has been manifested in the growing proportion and importance of IT related courses in the curricula of architectural schools. Many schools have increased IT content in their curriculum and are investing resources to acquire computing facilities to ensure that they provide their students with the necessary skills and competitive advantage. At the same time, the debate within the profession has shifted from the rel-

evance of drawing in pencil and ink to the relationship between digital media and architecture itself. Furthermore, how are computers transforming the way architects learn to design and build? (Cuff, 2001)

At the architecture undergraduate program of KFUPM and similar to most of the architecture schools, the design work in final reviews of projects done by architecture students is increasingly if not entirely computer-generated with colourful and wonderful presentations. However, it was observed that the focus seems to have changed from quality design to quality presentations. Focusing on critical thinking, creativity, design analysis, climatic and contextual considerations, and concern of structural and building systems seems to be paying the cost of shifting the focus to digital presentations. This is rather an alarming remark about the impact of digital-based curriculum on students' learning in architecture. Therefore, it has become imperative to analyse the impact of digital-based curriculum on undergraduate students' learning in architecture at KFUPM and to identify ways and means to enhance student's learning.

2. Digital technology and its impacts on students' learning

Pedagogy is any conscious activity by one person designed to enhance the learning of another (Mortimer, 1999). While pedagogy can be a personal matter it is more often conceived as the art or science of teaching; a set of principles and practices to improve learning. Educational technology, as a subset of pedagogy, is the sound use of any technology to support and improve learning. Information technology, on the other hand, focuses more on the digital delivery of information. Technical issues tend to take precedence. Christie and Ferdos (2004) argued that educational and information technologies cannot be separated. For better or for worse they impact upon one another. When one seeks to improve learning using digital media, pedagogical considerations are always an issue. The same fundamental questions that are asked of traditional university pedagogy need to be asked of digital-based curriculum but, in addition, the potential for a radically different, more innovative pedagogy has to be explored. Good pedagogy can inform and be supported by good IT. Poor pedagogy can subvert the very point of using good IT. A combination of bad pedagogy and bad IT is a disaster for the future of students' learning. Tien and Fu (2008) found that most undergraduates perform at the middle average level in terms of IT knowledge.

Ever since computers were deployed in earnest in the 1960s, researchers have been trying to use information technology to improve learning. And yet, except for a few cases, there is little proof that such exercises actually improve learning (Dertouzos, 1997). A major problem many researchers face

in this area is the difficulty in isolating and quantifying learning improvements resulting from the use of information technology among a myriad of other factors. Thus, one has to evaluate possible benefits that information technology can provide for delivery of education at a conceptual level. To measure the impact of new information technologies on delivery of education, one can look at how advances in information technology can enrich or facilitate various facets associated with delivery of education. Some of the major areas are providing access to information, improving communication means with a human tutor, customising information provided to a student based on students past performance and using specific information presentation schemes to enhance understanding (Ginige and Ginige, 1998).

2.1 DIGITAL-BASED ARCHITECTURE CURRICULUM AND STUDENTS LEARNING

The inclusion of advanced IT in Architecture curriculum depends on pedagogical ways through which technology can be used in interacting with demanding clients and society, delivering knowledge to learners or in representing ideas and alternatives through analysis and critiques. Kalay (1986) analysed the impact of Computer Aided Design (CAD) on architectural design education; in which he even asked if CAD had any impact at all. Kalay presented the following justifications for CAD in schools of architecture across the USA; (a) it assists students in reducing difficulties of expressing certain architectural forms, (b) it allows students to explore more alternatives and arrive at better solutions in a shorter time, (c) it allows students to appreciate the visual and numerical implications of the design decisions and to integrate aspects of e.g. (of cost, energy) into designs, and finally (d) it allows students to explore “new” ideas without fear of having to reproduce an entire drawing should things go wrong. But Howes, (1986) pointed to a report which indicated that the level of computer utilisation in architectural education was quite low compared to other disciplines. Howes also proposed an uncompromising minimum level of contact with computers by students of architectural design (they should understand and appreciate what the computer could do especially in the practical world of design at the least); hence it was agreed in general that all graduates ought to be computer literate and would be expected by the industry to be able to approach keyboards and manuals with little fear. As such, the minimal contact should ideally include ‘hands-on experience in drafting’ even if it is at the basic level.

A decade later, Qaqish and Hanna (1997) conducted a worldwide questionnaire survey on the applicability of computers in architectural education. Their survey covered 51 institutions in seven countries and among their key

findings is that virtually all (92.15%) the of studied institutions had CAD programs in their curricula that were implemented for over 13 years as of the time of the survey; which was quite a significant improvement on the scenario a decade earlier. 42.63% of respondents could be regarded as CAD users while 57.37% were users of traditional media. As of that time, only 31% of respondent institutions had introduced virtual reality into their curriculum. Furthermore, Kvan (2000) addressed design learning and illustrates how computer tools have been used to support learning. Pentilla (2003) summarised the analysis of data on European architecture schools, collected in the eCAADe-conferences during the 1990s. Computer-Aided Design has developed into architectural information and communication technology (ICT), to become commonplace in architectural education. However, the general held views on new media use in the schools seems to be slightly optimistic. Most recently, Gecu and Ozdener (2010) demonstrate that using dynamic geometry software has a significant place in geometry instruction and results in improvements in achievement and retention of knowledge.

3. Impact analysis of digital-based architecture curriculum students' learning

In order to assess the impact of current digital-based curriculum in architecture at KFUPM on students' learning primarily from students' perspectives, a structured questionnaire sample was developed and a small group of junior and senior students enrolled in the undergraduate architecture program at KFUPM was interviewed for a pilot study to fill out the structured questionnaire sample in order to clarify the issues addressed in the questionnaire in case of ambiguity and introduce necessary modifications prior to conducting the actual survey. The final structured questionnaire was filled out by current (junior and senior) students from the undergraduate architecture program in order to analyse the impact of current digital-based curriculum in architecture on students' learning primarily from students' perspectives. Other structured questionnaires were developed to acquire graduated students, teachers and industry perspectives on this regard. All structured questionnaires include close-ended and open-ended questions. Due to the limited length of this paper, the focus will be on analysing the impact of digital-based architecture curriculum on students' learning from students' perspectives.

3.1. KEY FEATURES OF THE DIGITAL-BASED ARCHITECTURE CURRICULUM AT KFUPM

The focus of the curriculum is on computer aided modelling and presentation

rather than on computational designing. Digital-based courses in the architecture curriculum are taken as courses with information technology specified as a major component of their teaching and learning process. Such courses are reflected in the curriculum as both core and elective courses. The total credit hours of the core digital-based architecture courses represent 10% of the curriculum requirement of the program and are as follows: Computer Aided Architectural Design, Virtual Reality in Architecture, Virtual Design Studio, and Construction Documents. There are three elective courses that fall into the category of digital-based architecture courses and are as follows: Computer Presentation Technique, Knowledge Based Systems in Architecture, and Special Topics in Computer Aided Design.

The curriculum requires a student specialising in CAD minor to take at least two of the CAD elective courses. A student completing the program but specialising in an option other than CAD would take digital-based architecture courses that represent a minimum of 10% and a maximum of 11.33% of curriculum requirements. A student specialising in the CAD option would take digital-based architecture courses that represent a minimum of 12.66% and a maximum of 14% of curriculum requirement. This analysis raises questions of the amount and representation of digital-based architecture courses required to constitute a focus in an architecture program and also of the percentage of curriculum requirements that would constitute a minor area of specialisation.

3.2. GENERIC IMPACTS OF DIGITAL-BASED ARCHITECTURE CURRICULUM ON STUDENTS' LEARNING

The students were asked to respond to sets of questions regarding the impact of IT on their learning. Figure 1 shows the responses received. Most noticeably among the responses are the following: 56% 'agreed' that use of IT enhanced their learning, while 32% 'strongly agreed' to this proposition. 44% 'strongly agreed' that IT enhances their designs while 32% 'agreed' to this; meanwhile 12% 'disagreed' completely with this suggestion. However, as for the whether IT enhances their presentations, 76% of all students 'strongly agreed' while 20% 'agreed' with this notion. 44% 'strongly agreed' that core courses should inculcate the use of IT; while 24% 'agreed' to this suggestion. 16% were indifferent to this suggestion and the same proportion of students 'disagreed' totally with this idea. As for use of IT in design studios, 44% 'strongly agreed' while 20% were 'neutral', while equal numbers (16%) both 'agreed' and 'disagreed'. 48% of respondents 'strongly agreed' that email is important for communication, and 36% simply 'agreed' to this notion while 16% were 'neutral'. When it came to the issue of whether the web enhanced their learning, most (36%) were indifferent or neutral to this suggestion. However, 32% 'agreed'

while 24% ‘strongly agreed’ to this concept. Meanwhile 40% of respondents ‘strongly agreed’ that they were skilled enough to use basic web-based learning methodologies; 32% ‘agreed’ while 12% disagreed that they possessed this ability.

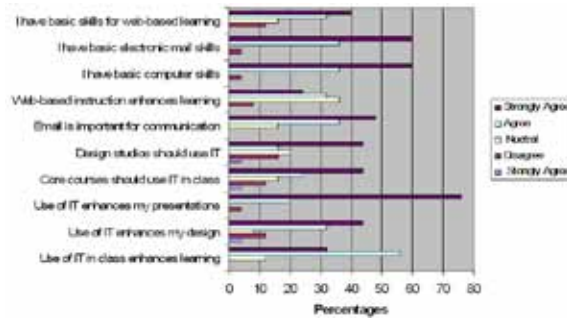


Figure 1. Students' responses on the generic impact of IT on their learning.

3.3. SPECIFIC IMPACTS OF DIGITAL-BASED ARCHITECTURE CURRICULUM ON STUDENTS' LEARNING

3.3.1. Levels of achieving better understanding of the architectural issues of buildings

Students were asked to rate how much they agreed that certain architectural issues were better understood through use of digital-based architecture curriculum (in instruction, resources and delivery). Understanding is exemplified in four measures: Reflective (monitoring and thinking about); Constructive (integrative, deep and creating own response); Thoughtful (deep processing); and Creative (exploration and generation of innovative ideas). The architectural issues include: form, purpose, spaces, circulation paths, artificial light, air quality, social context and scale. The results illustrated in Figure 2 show an agreement that a better understanding of the architecture of buildings is achieved through the digital-based architecture curriculum especially of high percentages for the issues of form and scale. On the other hand, there is a disagreement in the students' responses for achieving better understanding of the architecture of buildings in the current digital-based architecture curriculum on the issues of purposes of the building (12% strongly disagreed); air quality (16% strongly disagreed); and social context (16% strongly disagreed). There is however some students opted to stay neutral when rating some architectural issues such as purpose, spaces, circulation and use of artificial lights, which all had 12% neutral rating from respondents who could not tell whether or not

these architectural were better understood by the use of digital-based architecture courses.

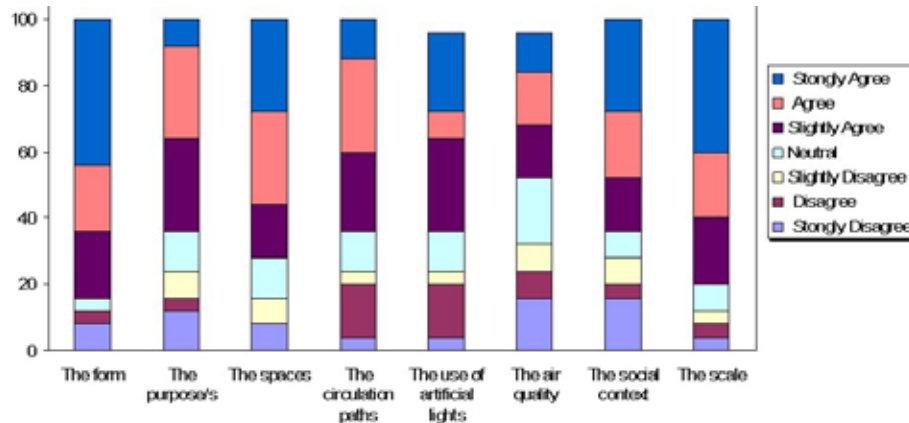


Figure 2. Students' responses on how one set of architectural issues were better understood through use of digital-based architecture curriculum.

Similarly, students were requested to rate how much they agreed that another set of architectural issues were better understood through use of digital-based architecture curriculum (in instruction, resources and delivery). The second set of architectural issues include: colour scheme, immediate surroundings, views, construction methods, materials and texture, cost, context and air movement/ventilation. Figure 3 reveals that there is a general agreement with this notion for colour scheme, immediate surrounding and views. Quantitatively, 8%, 32% and 24% were recorded for colour scheme in terms of slightly agreed, agreed and strongly agreed with impact of digital-based architecture curriculum in understanding colour scheme. Meanwhile immediate surrounding had 20%, 24% and 24% respectively; views had 16%, 24% and 20%. However, construction methods, materials/texture, cost, context and air movement/ventilation had more respondents opting to strongly disagree, disagree or slightly disagree with the notion that digital-based architecture curriculum has aided their comprehension of design through these architectural issues. Specifically, construction method and context had 20% of respondents each, strongly disagreeing with the notion. 24% of respondents strongly disagreed that the utilisation of digital-based architecture curriculum enhanced their understanding of the cost aspect of architecture.

3.3.2. Impacts of media qualities on understanding architecture

The impacts of media qualities on students' understating and learning archi-

texture within the digital-based architectural curriculum was put to test by subjecting several factors of media qualities to the scrutiny of students. They were asked to assess the following media qualities: accessibility of information, clarity of information, interesting/appealing representations, coherence/correctness of information, organisation/structure of information, completeness of information, immersion, and others (time-saving). The factors of accessibility of information, clarity of information, interesting/appealing representations had 12%, 4% and 20% votes respectively from respondents who strongly agreed with their influence on understanding the architecture of buildings as shown in Figure 4. Nevertheless these same factors had 4% 12% and 4% respectively votes from respondents who strongly disagreed with these respective factors having an influence on the understanding the architecture of buildings.

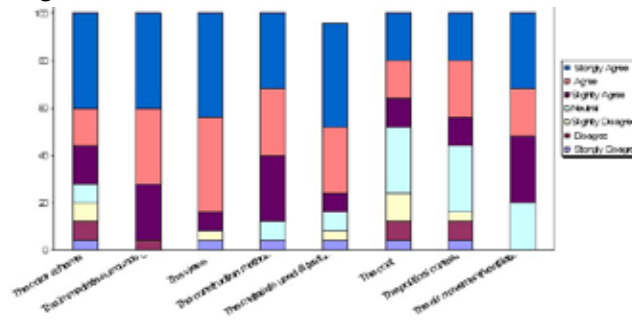


Figure 3. Students' responses on how another set of architectural issues were better understood through use of digital-based architecture curriculum.

4. Improvement plan for the current digital-based architecture curriculum at KFUPM

Based on a thorough review of the impact analysis of current digital-based architecture curriculum on undergraduate students' learning at KFUPM, a set of three initiatives has been identified to improve and enhance students' learning. For each proposed initiative, priority, duration, responsibility for implementation, tasks for the proposed initiative, and key performance measures are articulated. The set of three initiatives includes:

- Establish a clear and sound vision for IT adoption in the architecture curriculum at KFUPM
- Develop a change scheme to introduce CAD as design medium in the architecture curriculum in a set of carefully selected Design Studios to practically shift the utilisation paradigm of CAD from drafting and modelling to substantially include designing and creativity.

- Introduce curriculum revisions to accommodate advanced utilisation of IT for real life situations and industry needs, e.g. virtual collaboration and group work, office automation, construction cost, and management of building life cycle, etc.).

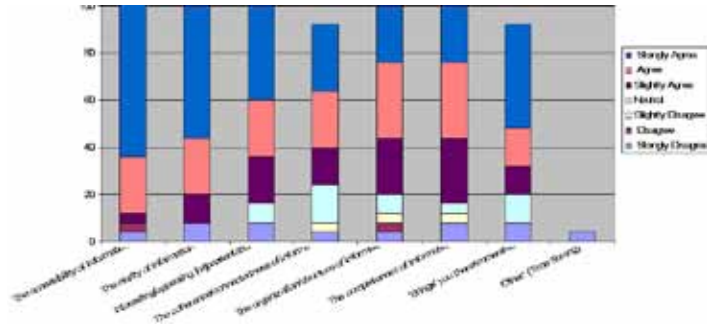


Figure 4. Students' responses to the importance of media quality factors in understanding the architecture of buildings through use of digital-based architecture curriculum.



Figure 5. An example of the proposed initiatives in the improvement plan of current digital-based architecture curriculum at KFUPM.

5. Conclusion

The inclusion of advanced IT in architecture curriculum depends on pedagogical ways through which technology can be used in interacting with demanding clients and society, delivering knowledge to learners or in representing ideas and alternatives through analysis and critiques. Therefore, it is quite important to analyse the impact of digital-based curriculum on undergraduate students' learning in architecture and to identify ways and means to enhance student's learning. The findings of an impact analysis of digital-based curriculum on students learning in architecture showed that there is a need to: establish a clear and sound vision for IT adoption in the architecture curriculum, develop a change scheme to introduce CAD as design medium in the archi-

itecture curriculum in a set of carefully selected design studios to practically shift the utilisation paradigm of CAD from drafting and modelling to substantially include designing and creativity, and introduce curriculum revisions to accommodate advanced utilisation of IT for real life situations and industry needs. It is anticipated that the process and results of such analysis are not only potentially useful to KFUPM but also the benefits can be extended to the many of the digital-based architecture curricula around the globe.

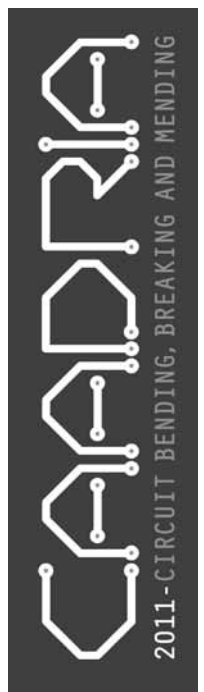
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THEORY, PHILOSOPHY AND METHODOLOGY
OF COMPUTATIONAL DESIGN RESEARCH



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59.	One-behind-the-many metaphysics and the myriad things <i>Thomas Fischer</i>	623
60.	Constructive interpretation with examples from interpretation of floor plans <i>Nick Kelly, John S. Gero and Robert Saunders</i>	633
61.	The gardens revisited: The link between technology, meaning and logic? <i>Gabriela Celani, José P. Duarte and Carlos V. Vaz</i>	643
62.	Architectural space information scale: A new way of understanding architectural space <i>Wei Zhang and Yiping Wang</i>	653
63.	A is B, displacement: Exploring linking patterns within metaphor in the design process <i>Chia-Hui Lo, Ih-Cheng Lai and Teng-Wen Chang</i>	663

ONE-BEHIND-THE-MANY METAPHYSICS AND THE MYRIAD THINGS

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Abstract. In this paper I identify the metaphysical assumptions underlying much of the science, technology, education and design thinking practiced in contemporary CAAD research in Asia as a Western import. Citing some traditional Asian complements to such assumptions and offering an alternative model, I hope to enable a discussion about assumptions underlying our field as well as an awareness of different standards of thought and responsibility between which CAAD research in Asia may operate.

Keywords. CAAD philosophy; blueprint; general; particular.

1. Introduction

Having come to Computer-Aided Architectural Design Research and to Asia in short succession in the late 1990s, it took me a few years to realise that in those years I underwent two culture shocks at the same time. Continuing to learn to operate in both cultures, I enjoy my involvement in Computer-Aided Architectural Design Research in Asia (CAADRIA), where the two cultures converge. At the same time, I continue to be surprised that our field is investigating and shaping the characteristics and roles of the digital computer, of architectural design, of research and of education in our enterprises; but not so much the characteristics and roles of Asian traditions of thought. I agree with Watts (1995, p. 82) that studying a culture other than one's own can help one in understanding one's own culture and its underlying assumptions. In this paper I present some of my own advances in this respect regarding the two-tiered metaphysics of the Western world: the notion that the world we observe and with which we interact is determined by ulterior principles and forces. Somewhat along the lines of Kuhn's (1996, pp. 10ff.) discussion of the role of scientific *paradigms* and Lakatos's (1970, pp. 133ff.) notion of *hard cores* of

research programmes, I argue that CAAD researchers form a community with its own culture, which is based not only on certain intellectual paradigms, but, more fundamentally, also on cultural assumptions that remain largely unchallenged and that are protected by the members of the community who may or may not be explicitly aware of them.

Basic cultural assumptions play an important social role by aligning values, judgements and practices within groups and by allowing consistency within cultural bodies of thoughts and ideas. They offer these benefits without necessarily being made explicit and without all members of the groups facilitated by them being consciously aware of them. On the contrary, members of a given culture are, I believe, unlikely to be consciously aware of all the assumptions upon which the culture is based from their insider's perspective. We may, for example, pursue technological progress because we subscribe to the cultural assumption that time takes the shape of a directed arrow, that fate is in our hands, and that our choices and actions may bring about more desirable futures. For such social alignment to happen, it is not necessary for all parts of the group to explicitly realise these underlying assumptions.

Just as they offer benefits, implicit cultural assumptions also entail risks and potential downsides. They may be accepted simply due to the (perceived) lack of alternatives, protected to avoid inconsistencies, or defended where potential challenges to them are seen as threats to cultural accomplishments and intellectual conveniences built upon them. Such adherence to cultural assumptions may not always be the most preferable, most beneficial or most interesting option, for there may be other, less constraining sets of assumptions available elsewhere, which could allow for worthwhile alternative action and judgement. Understanding, accepting and adopting an alternative cultural perspective, with different values and different basic assumptions, is challenging because such an alternative likely appears in direct opposition or as a threat to one's own intellectual framework, possibly inviting cognitive dissonances. This is particularly the case for those whose cultural assumptions require judgements to be made on a mutually exclusive basis (thereby dictating the view that *either* this culture is right *or* that culture is "right").

In the following exposition, I juxtapose a Western metaphysical assumption with Asian alternatives, not in the spirit of competition, but in the spirit of plurality and of finding *an increased number of choices* (von Foerster, 2003, p. 295). This paper is thus *not* a statement *against* the Western thinking style. It is an argument *for also* considering alternative thinking styles native to the CAADRIA region. Hopefully, this can allow more informed choices between them in different circumstances. Two texts that inspired me to come to our field serve as my points of departure.

2. DNA and parameters

Frazer (1995) envisions a new architecture that is not based on blueprints specifying the form of finished products, but on a “coded set of responsive instructions”, i.e. a “bag of seeds”, describing the manoeuvres performed in the process of architectural production as well as potentially the processes of architectural self-maintenance and self-reproduction. Quoting others, Frazer notes that in contrast to the DNA blueprints found in biology, “an architect’s blueprint is a specific one-off set of plans” (Frazer, *ibid*, p. 11), somewhat analogously to Helmut Jahn’s observation that “Every building is a prototype. No two are alike”.

Burry (1999) proposes a parametrically driven approach towards geometric modelling, in which a well-defined geometric schema is numerically controlled using explicit parameters as a method to explore geometric variation without accidents. The purpose is to enable design processes that satisfy the (scientific) criterion of repeatability.

Both Frazer’s and Burry’s proposal have proved profoundly influential in advancing the role of the computer in CAAD beyond that of a fancy drawing board. Attributing primacy to rational, symbolically premeditated coding ahead of concrete instantiations, both proposals maintain the basic two-tiered metaphysical architecture of Western thought (Ziporyn, 2008, p. 402).

3. Metaphysics

This two-tiered metaphysical architecture of thought is essential to modern, Western thinking, particularly in science, design and computing, while it is downplayed in important Asian traditions of thought. This paradigm is implied in the term “one-behind-the-many metaphysics” (Ames and Hall, 2003, p. 14): the notion of transcendent principles underlying worldly manifestations, generatively or descriptively or both. With ancient roots, such as Plato’s Theory of Ideas (Ross, 1951), this paradigm is virtually ubiquitous in the modern world and largely invisible to most who were raised under its influence. It is integral to Abrahamic religions (Islam, Judaism and Christianity: divine Truth revealed through scripture affecting the World), and thus also to Western traditions of education (transferrable knowledge behind capability), to architecture (artistic ideas behind buildings, see Mitchell, 1990, pp. 37ff.) and to the Western scientific research tradition (principles and laws behind observable phenomena). From this basis it inspired design (concepts behind innovations) as well as computing (code behind runtime operation), computer interface design (script behind performance, see Laurel, 1993, pp. 14ff.) and programming language paradigms, in particular the object-oriented programming

paradigm (classes behind instances) and XML, which are part and parcel of Building Information Modelling, as well as computer-aided design paradigms including generative design (genotypes behind phenotypes) and parametric design (geometric schemas and variable parameters behind variant form).

The above examples have in common the pattern of generalised, relatively abstract symbolic descriptions being conceived as determining relatively concrete instantiations. Symbolic descriptions (stock market indices, programming code, architectural drawings or this sentence, to name some examples) are omnipresent in contemporary “knowledge culture”. With these descriptions comes the temptation to mistake them for the phenomena they describe, i.e. taking the “map” for the “territory” (Korzybski, 1933, pp. 750ff.), which leads to profound distortions of our relationships to each other and to our material environments (Watts, 1994, p. 106).

Asian traditions – such as Taoist and Buddhist philosophy – opt not to prioritise such a two-tiered paradigm. This is expressed in the (somewhat corresponding, but precisely not metaphysical) Chinese description of the phenomenal world as “the Myriad things” (萬物, literally: “the 10,000 things”, where 10,000 stands for a very large quantity, figuratively: “every-thing”, see Ames and Hall, 2003, pp. 130). The Myriad things are thought of as existing *en par*, interdependently and each on its own. This view involves more interest in particulars than in their generalised analytical descriptions and symbolic representations of their structure, of their origins and so forth. This is not to say that civilisations in these Asian traditions are immune to confusing “map” and “territory”. They strive, however, for forms of enlightenment that address this issue. Hesse (2005, p. 44) describes the moments following the awakening of Siddhartha as follows: “Blue was blue, river was river, and if also in the blue and the river, in Siddhartha, the singular and divine lived hidden, so it was still that very divinity’s way and purpose, to be here yellow, here blue, there sky, there forest, and here Siddhartha. The purpose and the essential properties were not somewhere behind the things, they were in them, in everything”. (In my view Aronofsky’s 1998 movie π has the same theme.)

Zen Buddhism distinguishes four realms of increasingly higher intellectual acclaim (四法界): the realm of the particular, the realm of the abstract, the unobstructed transition between particular and abstract and finally the unobstructed transition between anything particular and anything else particular. According to this highest level of insight, each observable particular is seen not as a manifestation of prototypical principles that are abstracted from or hidden behind the world of appearances. Each observable particular is seen as what it is and as related to, and mutually interdependent with everything else. This is however not to say that symbolic abstraction is entirely dismissed in

favour of concrete particulars. “Map” and “territory” are not divorced from one another and thus not caught up in competing truth claims. Zen culture, for instance, expresses inconspicuous particulars while at the same time attributing to them symbolic significance. In this way, a Japanese *tatami* mat is both a particular thing and an abstract unit of measure. Consider also the most important column in the traditional Japanese house, the *tokobashira*, which performs no static function but a symbolic function, by introducing a unique and particular organic shape into the otherwise regular configuration of the house. Taking the abstract and the particular as two particular ways of looking at particular things, Zen, like Daoism (Ames and Hall, 2003, pp. 24-27), accords primacy to the particular.

4. Design concepts, scientific principles and “knowledge transfer”

Where writings, numbers, codes and so forth are taken as passageways connecting transcendent causes such as divine or scientific “truths” with effects in the world of our experience, the relative neglect of the world of our experience can lead to the assumption of “transferability” of that which is expressed symbolically. A case in point is the Western/modern notion of teaching and learning as “knowledge transfer”, analogous to banking transactions (Freire, 2009, pp.71ff.). This is indicated in the word *seminar*, which is related to insemination, i.e. to the transfer of seeds from an outside origin to an inside destination. Knowledge is thus regarded as if it was a commodity that is transferrable from A to B. This is depicted in the image of the Nuremberg funnel, through which teachers pour knowledge into learners’ heads. The teacher transfers knowledge conceptualised as seed kernels to the learner, an initially empty vessel, in whom wisdom is expected to sprout.

In the design fields as well, concepts are thought of along similar lines as indicated in the similarly sexual understanding of *conception* as a reception of seeds. Abstract notions, not much unlike platonic ideas, are identified as inspirational drivers of creative processes resulting in worldly manifestations. Design concepts (functioning prescriptively) are thus the generative mirror-images of science’s (descriptively functioning) explanatory principles. The two-tiered metaphysical structure hence projects the ultimate authority and source of explanation, knowledge and inspiration to an ulterior location beyond the apparent world and outside of the reach of human observers such as learners, designers and scientists. Despite some acknowledgement that map and territory are connected via largely arbitrary (essentially creative) choices, the formally defensible match of symbolic/transferrable descriptions and respective phenomena in the world is assumed to constitute “Truth”. The human observer thus finds herself in a passive spectator’s position, epitomised

in the natural sciences' ideal of objectivity. General principles affecting the world from beyond are emphasised while subjective encounters with particulars are downplayed. Thus, Western scientific thought differs not only from traditional Asian thought, but also from the concerns of applied designing. Buchanan (1995, p. 15) points out: "...the designer must discover or invent a particular subject out of the problems and issues of specific circumstances. This sharply contrasts with the disciplines of science, which are concerned with understanding the principles, laws, rules, or structures that are necessarily embodied in existing subject matters".

Deploying computers in architectural design under the scientific paradigm in Asia may hence not necessarily harmonise with the ways in which architectural traditions emerged and developed in the region. Conversely, not all Asian approaches to producing architecture (or novelty in general) may harmonise with the paradigms of thought and the standards of appreciation that were, and continue to be, imported from the West. (My contrasting of Asian and Western thought here serves to make my point clearly. I am referring to subtle tendencies, not a universal, clear-cut distinction. There are outstanding design educational and architectural thinkers in the West who are arguably compatible with traditional Chinese or Japanese thinking, such as Peter Zumthor or Johannes Itten.)

Consider the following two approaches: one architect visits the site, investigating what response it may call for, and designs a particular building form to fit the given site/landscape/context. Another architect conjures up a generic housing concept and has it implemented by adapting (bulldozing) the particular landscape(s) found at the site(s) to accommodate it (Watts, 1995, pp. 14-15). Or: one computer-aided designer hacks rough code and interfaces mutually incompatible tools simply well enough to address the challenge at hand, to achieve a viable building form, while another (maybe with a view to formal examination or publication review) prioritises exclusivity in tool choice, algorithmic well-formedness, optimisation, exhaustive searching of "solution spaces" or formal proof over viability of the building forms achieved in these ways. The distinction in both of these examples lies in whether the general is taken as an instrument in the pursuit of the particular (corresponding to the tenets of the Myriad things) or whether the particular is taken as an instrument in the pursuit of the general (corresponding to the tenets of two-tiered metaphysics).

Design researchers, caught between these two agendas, must resort to trickery to satisfy the conflicting criteria of both sides, such as claiming concern for "the user", who is sometimes a plural posing as a singular and sometimes a singular posing as a class.

5. An epistemological model and a proposed alternative

Let us consider the relation between the observer (you, me, anybody), the observed world and descriptions of the observed world – i.e. the triangle formed between describer, described and description, as originally proposed by Gottlob Frege (Glanville, 1975, p. 192 ff.). Umpleby (2007, p. 4), based on von Foerster (1971), points out that this triangle (left of figure 1) allows the locating of different linguistic perspectives (syntactics, pragmatics and semantics) along its three edges. Umpleby further notes that the philosophical perspectives of (British-originated) empiricism, (US-originated) pragmatism and (continental-European-originated) idealism can be located correspondingly. This elucidates corresponding tendencies in CAAD research towards, for example, application and fabrication on one side of the Atlantic and towards theory-building research on the other side. Moreover, I believe the triangle allows the relative positioning of research *about* design, research *for* design and research *through* design described (in slightly differing terminology) by Frayling (1993/94) and Findeli (1999).

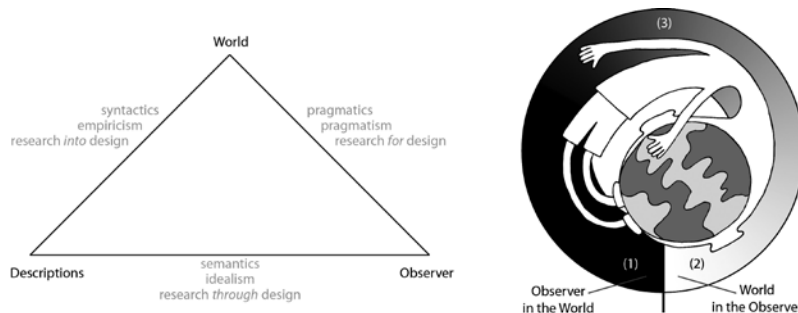


Figure 1. Epistemological triangle based on Frege (left) and proposed alternative (right).

Each of the three edges in the triangle can stand for a basic cultural assumption of the West, each formed as a dual schism: world or/outside/versus observer, observer or/outside/versus description and description or/outside/versus world. From the perspective of the observer's vertex, the two remaining vertices in the triangle form the two-tiered Western metaphysical structure: The world and, separate from (transcending) it, descriptions of the world. This divorce, evident in various aspects of the Western tradition of thought, is indicated in the word science (derived from Indo-European root *skei*: to separate; similarly to schism, schizophrenia etc., see Bröcker, 2004, p. 20). Pre-modern traditions of Asian thought tend to avoid such divisions. In these Eastern traditions (as well as in strands of cybernetics and general systems theory), the observer (oneself or anybody/anything else granted a vantage point similar

to one's own) and the world occupied by it form an inseparable unity. The observer observing the Myriad things is herself one particular of the Myriad things, which in turn are inseparable from each other and constitute the world. The non-human world is thus not necessarily to be subdued by man, conquered and exploited, but forms an integrated whole with each member of its population. This has implications for how one thinks about whether and how change is to be put into the world – i.e. designing. In “traditional” cultures, care for oneself and care for the environment are indistinguishable. Recently, this state of affairs has taken a peculiar turn. As some in the West are waking up to the possibility of non-dualist, non-hostile world-observer relationships (Watts, 1995, pp. 1-34), ironically, Asian cultures modernise and “develop” to an exploitative attitude towards the environment. While many begin to realise that what is done to our world is done to ourselves, many planners and designers have yet to realise that much of our modern intellectual and technological toolbox derives from a metaphysical mindset based in the opposite presumption. As the edge connecting the world and the observer in Frege's triangle collapses from a traditional Chinese perspective, so does the edge connecting the world and its descriptions: Chinese script is said to have been invented at the order of the Yellow Emperor by Cang-jie 倉頡 around 2650 B.C. When later, during the Han dynasty, Chinese philologist Xu-shen 许慎 described Cang-jie's act of bringing characters into the realm of humanity, he used the verb *zuò* 作. This verb, which today is commonly translated as “to do”, in Xu-shen's time was translated as “causing to arise” (from the patterns of nature). The word was used in the Warring States and Han periods to describe the sages' invention of culture (Puett, 2001, pp. 22-23). In this narrative, script is not presented as a transcending contrivance and *zuò* does not imply a separation or a discontinuity between description and described, as it is understood in the West. On the contrary, *zuò* leaves iconic signifiers and what they refer to in a close correspondence. In this view, observable phenomena in the world may be more readily approached as signs, while symbolic signifiers and descriptions (characters, poems) may be more readily approached also as observable phenomena: The distinction blurs. Signification enters the domain of subjective choice and is not taken as a transcendent causal and explanatory force beyond the world of appearances. Recognising design as being concerned with the particular, and recognising generalised principles as human-made descriptions, the model on the right of figure 1 (based on Fischer, 2010, pp. 614 ff.) abandons the two-tiered metaphysical perspective and, along with it, transcendent causal and explanatory authority. It accommodates multiple epistemological positions: The bottom left (1) corresponds to the realist position that the observer is inside a found world (the world is the cause, experi-

ence is the effect). The bottom right (2) corresponds to the idealist position that the world is made inside the observer (experience is the cause, world is the effect). The top (3) corresponds to the position that world and observer interact in a circularly-causal fashion, each retaining traces of their interaction. The model offers observers representing any of these positions a map to locate their concerns in given contexts and to negotiate and evaluate the role and value of their “Myriad realisations”. Positioning a concern at the realist end of the gradient implies a desire for realisation(s) in the world (controlling). Positioning a concern at the idealist end of the gradient implies a desire for realisation(s) in the observer (learning). Positioning a concern at the centre of the gradient implies a desire to include enough instances of controlling and of learning within the scope of that concern to allow new matching sets of internal and external realisations to appear. I regard all realisations brought about everywhere along the gradient as particulars. Some realisations may be generalisations of prior realisations and may thus be viewed as descriptions: explanatory, analytical, evaluative, predictive, prescriptive, etc. models. I see the proposed model itself as an example of an explanatory description that, at the time of writing this, I place on the left side of itself because I aim to use it to put thoughts of mine out into (others in) the world. Generalised descriptions (one-behind-the-many realisations), such as speed limits, research methods, scientific paradigms or mass production facilities, are (hopefully sufficiently robust) pre-rational shortcuts. They offer simplicity and utility by generally justifying particular choices, and by eliminating the need to think about them. We thus make *responsible* choices precisely in the absence of general principles and outside of two-tiered metaphysics.

6. Concluding remarks

In thinking in two-tiered metaphysical terms, one implicitly accepts that good reasons and justifications for implied choices lie hidden behind the curtain of generalised description. One-behind-the-many generalisations eliminate the requirement to think about and to take responsibility for choices made. Every map that is abstracted from the territory lends itself to this use. While this may, in the case of good maps, lead to good choices, it almost certainly also leads to poor choosing due to the usually unquestioning re-use of choices already made by the map-makers. Science and digital technology, as they are commonly presented, reinforce this state of affairs. Is this an acceptable foundation for design? Should designing and design education not be first and foremost about thinking and accepting responsibility? Some aspects of design education recognise the shortcomings of generalisation, for example by preferring tutorial based education over mass lectures. More can be done. Our

field deserves a discourse about responsibility and standards for evaluating and appreciating the particular besides the general. Besides criteria like well-formedness, formal proof, optimization, exhaustive searches or tool efficiency, I see a need for the cultivation of personal rigour that takes into account the viability and value of particulars. Such standards are explained more convincingly (I argue) as coming spontaneously from our responsible interaction with the world rather than from behind a curtain.

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CONSTRUCTIVE INTERPRETATION WITH EXAMPLES FROM INTERPRETATION OF FLOOR PLANS

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Abstract. This paper describes the role that interpretation plays in facilitating situated design and presents an implementation that shows a system interpreting floor plans. Designers often see more in what they produce than they intentionally put there. Cognitive studies suggest that this helps develop design ideas. Interpretation is described as the use of expectations to construct an internal representation of an external representation (such as a sketch). An implementation is described. As an example of its capability the system, primed on floor plans, looks at a randomly generated image and can find a floor plan within it. The system produces different results with the same image if it has different expectations. This is used to discuss the notions of a space of possible designs and the two way relationship between expectations informing interpretation and interpretation changing the expectations (design ideas) of a designer. Further work is suggested and the ideas are discussed.

Keywords. constructive interpretation, situation, floor plan, reinterpretation, push-pull

1. Introduction

Whenever designers bring something from the external world into their internal world, interpretation is occurring, such as when designers read a design brief, consider their own work whilst sketching or observe the behaviours of a model. In each of these cases, designers interpret by constructing from their expectations. Their interpretation is affected by their past experiences (the limits of their knowledge) as well as their current cognitive state (how their

knowledge is being used).

The designer does not experience the world *tabula rasa* – there is pre-understanding, founded on experience, brought to the act of interpreting. What then is the relationship between the meaning that the designer constructs and the past experiences of the designer? Two computational models of the interpretation of floor plans are described in this paper, demonstrating what interpretation as the ‘construction of meaning’ looks like as distinguished from interpretation as the ‘processing of information’ (Bruner 1990). The work looks towards an understanding of the relationship between experience, expectation and interpretation in which: (i) interpretation is driven by expectations; (ii) expectations come from experience; and (iii) experiences occur through a sequence of interpretative acts.

1.1 INTERPRETATION IN DESIGN

It has been well recognised that the construction of interpretations is a part of design activity (Schön and Wiggins 1992, Suwa and Tversky 1997). The importance of these two studies on ‘kinds of seeing’ and ‘what do architects and students perceive in their design sketches’ is underscored by the fact that they are the two most cited papers within the *Design Studies* journal since 1990¹. In sketching, designers work with elements and the relationships between them. When they look at what they have sketched, they are able to see things in the representation that they did not intentionally place there. Interpretation becomes a way in which designers change their own idea of what they are doing (Suwa et al 2000, Oxman 2002). This can be observed in the “seeing-moving-seeing” of the design conversation, where discoveries within a sketch form the basis for future design actions (Schön and Wiggins 1992). This work is based upon a perceived need to explain this conversation of design at a deeper, cognitive level, in the language of concept formation and use. It is grounded in three cognitive frameworks: (i) Perceptual Symbol Systems (Barsalou 1999, 2008); (ii) Conceptual Spaces (Gärdenfors 2000) and (iii) Hierarchical Temporal Memories (Hawkins 2005).

An interpretation arises not just from the representation and the designer’s knowledge about the world, but also from ‘whereabouts’ within this knowledge the designer is at when interpreting; their current cognitive state or the *situation* they are in when interpreting (Clancey 1997, Gero 2007). In the implementation described here a situation can be considered as the world view resulting from the use of a number of concepts where concepts affect the use of each other (after Peng 2008). There is a bi-directional relationship between interpretation and situation: the situation that the designer is in changes their interpretation, and the act of interpreting can change the situation.

1.2 INTERPRETATIONS ARE CONSTRUCTED

A well-known children's game can be used to demonstrate interpretation as a constructive activity. In this game, one player scribbles some lines on a page such as that seen in Figure 1. The second player then has to draw a picture using the lines in the scribble. In order to do this they interpret the lines in the scribble 'as' something. For the scribble in Figure 1, as with any representation, there are many possible interpretations. In Figure 1, a drawing could be made using the lines of the scribble in which the circle becomes the wheel of a car, the eye of a bison or a hole in a cliff face – in each case the player has seen the drawing in such a way that an action is suggested. There are no limits to possible interpretations within the representation, only within the mind of the viewer. The example demonstrates that the meaning lies not in the representation itself but rather is constructed by the player looking at the scribble – and a different player will likely construct something different from the lines. In doing this the player is making use of their knowledge from experience in the world to construct an interpretation. In other words, "it's not what you look at that matters, it's what you see" (Thoreau 1851).



Figure 1. Lines on a page from which an interpretation can be constructed.

2. A computational example of construction

The same effect has been implemented in a constructive interpretation system. The system demonstrates that: (i) a randomly constructed representation is

given meaning by a system through construction from expectations founded on experience; and (ii) the same system with the same source and the same knowledge produces different interpretations depending upon the situation it is in when interpreting. The system is primed through experience of a number of floor plans, a sample of which is shown in Figure 2. The system uses a self-organising map (Kohonen 1989) to learn the different representations. It then scans the external representation, which in this case is a randomly generated set of marks upon a page, such as that seen in Figure 3(a), and constructs an interpretation using its expectations. In doing this the system constructs an interpretation that is both relevant to where it is at cognitively, its situation, and the source that is interacting with visually.

The development of situations is supervised in that floor plans are labelled with the architect responsible for them. Prior to interpreting the source, the system holds expectations from the situation. For example, if it is expecting a Palladio floor plan then it holds conceptual expectations related to this.

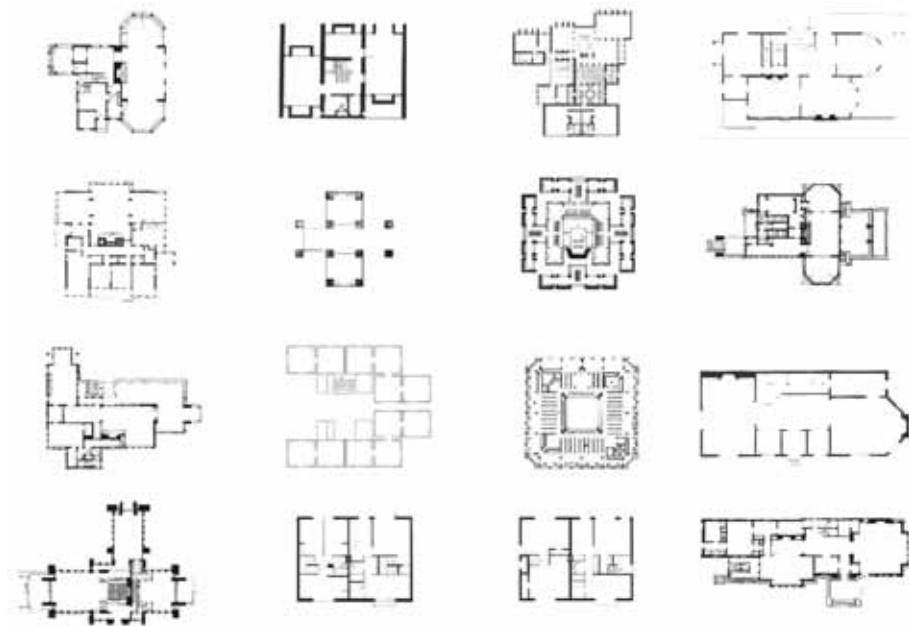


Figure 2. Samples from the set of floor plans used in the example.

A source is randomly generated as a set of pixels on a canvas, Figure 3(a), and the system saccades across the canvas, interpreting as it perceives, Figure 3(b).

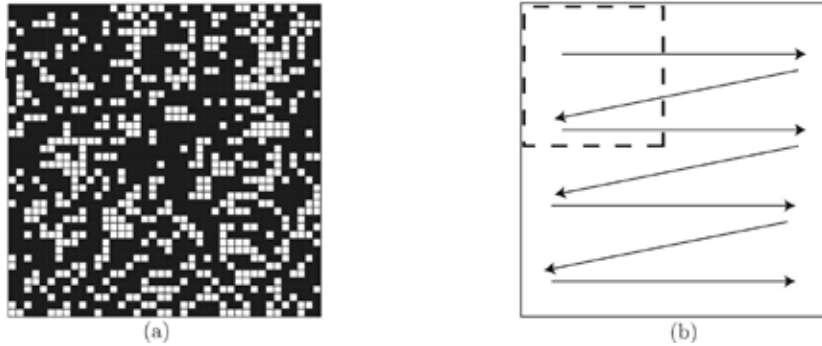


Figure 3. (a) A randomly generated source, (b) is perceived by saccading across the image in a pattern from left to right, with the system only ever perceiving 16x16 squares at a time.

The system attempts to construct from the available source data as it saccades, using its expectations. Figure 4 shows two examples of where a construction has occurred in two different runs of the experiment. In Figure 4(a) the system is expecting to find a Frank Lloyd Wright floor plan and in Figure 4(b) it is expecting to find an Andrea Palladio floor plan. The two runs have the same source and the same knowledge, but the situation that the system is in is different in the two runs. As a result, the constructed interpretation is very different - not only is the system constructing something different, but it is using a different part of the representation for construction.

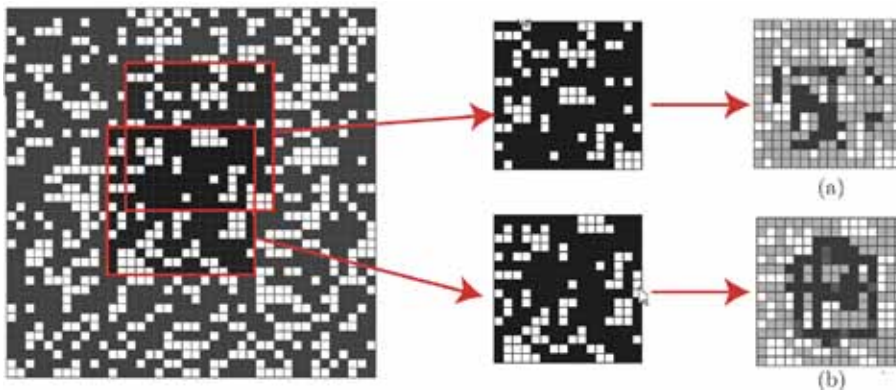


Figure 4. Two different constructions from the same source have resulted from two runs of the system with different expectations: (a) expecting a Frank Lloyd Wright; and (b) expecting an Andrea Palladio. The squares are black where construction from expectation has occurred.

The constructed representations are canonical representations of the initial floor plans that the agent was primed with through its experience. Figure 5(a)

and Figure 5(b) show what the system has ‘seen’ within a randomly generated source when expecting a Lloyd Wright and a Palladio floor plan respectively. In each case it has constructed an interpretation of something in the source as a floor plan from what is available. It has made this construction because of the expectations that it held. At this point in the saccade there was sufficient similarity for the system to be able to construct an interpretation from what it was expecting.

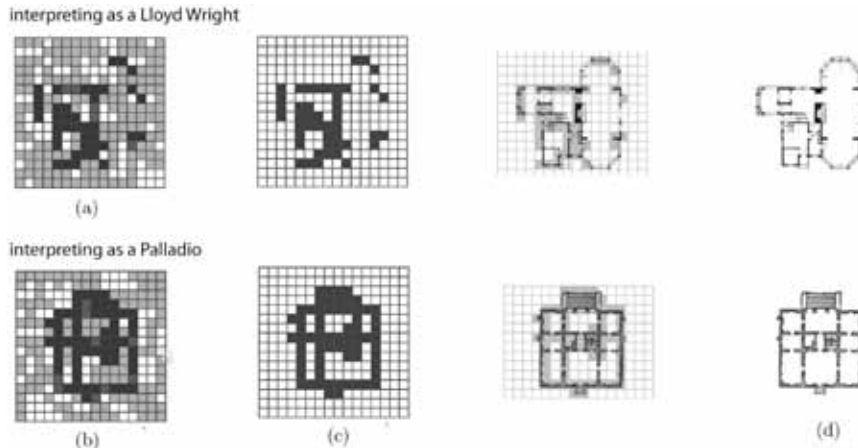


Figure 5. The two constructed representations are compared to the original representations that were part of the training set from: (a) a Frank Lloyd Wright; and (b) an Andrea Palladio. The images labelled (c) are representations of the concepts within the system that have been constructed. The images labelled (d) are the original representations used in the training set that goes to make up the viewer's knowledge about plans.

Two different interpretations are produced by runs in the system, but neither the knowledge held by the system nor the source has changed. The reason why the interpretation is different is that the system is within a different situation. This demonstrates that the expectations that the system holds are important in constructing an interpretation. The source being interpreted is a randomly generated bitstring. Because the system knows about floor plans, it is trying to construct what it is seeing as a floor plan. Often it is not able to construct anything meaningful.

3.2 A SPACE OF POSSIBLE INTERPRETATIONS

One way to describe what is occurring in the model is to introduce the notion of a space of possible interpretations. We can describe three spaces of possible interpretation based upon how they expectations are used referring to notions

of push and pull (Gero and Kannengeisser 2004):

- **Push-only interpretation.** In push-only interpretation, expectations are not utilised in producing an interpretation. The system uses everything that it knows about producing a representation from a source in the interpretation. In push-only interpretation the same knowledge (in the system) with the same source will produce the same interpretation. For example, a CAD system will represent the same file in the same way. Figure 6(a) shows this as a single space of possible interpretations bounded by the knowledge that the agent holds.
- **Pull-only interpretation.** In pull-only interpretation the expectations of a system are the basis for producing an internal representation. In pull-only interpretation every source is constructed from the expectations held by the system, regardless of how good a fit for the source these expectations are. Figure 6(b) shows this as a reduced space of possible interpretations. This space will be located in a different place in a different situation, meaning that the same source can produce a different representation.
- **Push-pull interpretation.** In push-pull interpretation an internal representation is constructed from expectations (as with pull-only) but push can occur where the expectations are not a good fit with the source. Figure 6(c) shows this as a reduced space of possible interpretations that can shift to another reduced space during interpretation.

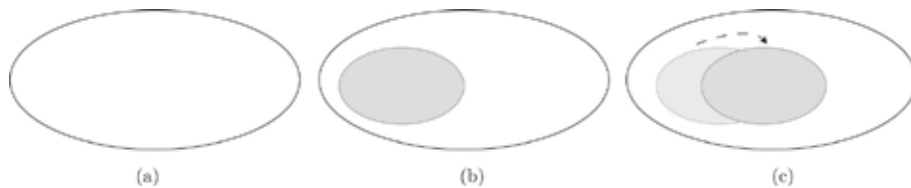


Figure 6. Three spaces of possible interpretations given: (a) push-only interpretation; (b) pull-only interpretation; and (c) push-pull interpretation.

3. Interpretation in the design conversation

In this first implementation the system was finding within a representation what it expected to find – an example of pull-only interpretation. In the design conversation, cognitive studies suggest that designers see using their expectations but also have their expectations changed by what they see (Suwa et al 2000).

A second implementation was developed in a similar environment to model

a design conversation in which the design agent begins with one notion of what it is doing which changes over time as it plays with ideas and interprets the external representation. Figure 7 shows a script typical of this implementation as the interaction between three worlds (Gero and Kannengiesser 2004). The agent begins with a set of explicit concepts and uses these in creating an external representation. For example, laying out a design using a grammar of shapes from Louis Khan floor plans. When it looks at the resulting layout it constructs an interpretation, which can lead it to bring concepts outside the situation into the situation. An example of this is a shape from a Frank Lloyd Wright floor plan being seen suggesting other similar shapes that could be useful for the design.

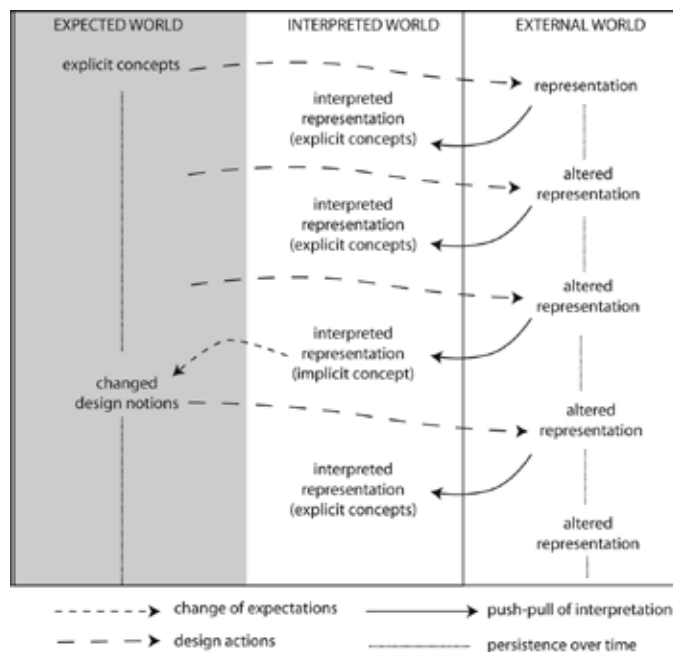


Figure 7. A design conversation as the interaction between three worlds, the internal, expected and external.

Implementing a design conversation with push-pull interpretation produces some phenomena observed in conceptual design activity. This can be described using the notions of situations and a changing space of possible designs (Coyne et al 1990). Within a situation a limited number of designs are possible. Figure 8(i) shows the movement to new designs within a situation. While this occurs, interpretation is able to occur through pull from expectation. When expectations cannot be met, the situation can change in one

of two ways, Figure 8(ii) through a change to the situation, or Figure 8(iii), through a change to an entirely new situation. These are the cases in which the designer has seen something within their work that they were not expecting. The model demonstrates one way in which this balance between pull from what is expected and push from the implicit expectations of a situation can be implemented.

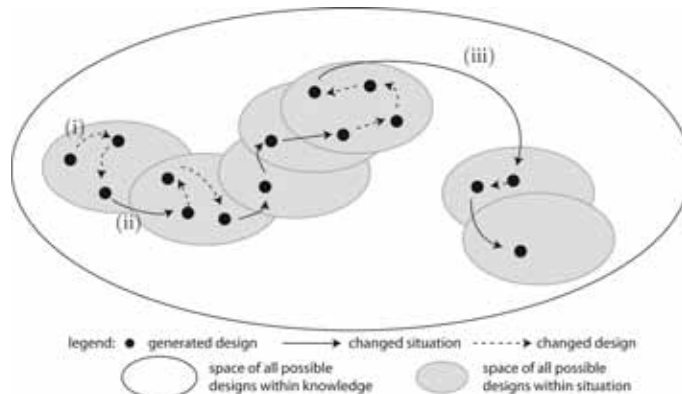


Figure 8. The changing space of possible designs in which interpretation can lead to: (i) new designs within the existing space; (ii) a shift to a changed space; and (iii) a shift to a new space of designs

Discussion

Interpretation pertains to the way that designers see things within their own work. The situation that a designer is in when they look at a representation affects the interpretation that they produce. The meaning of a representation is constructed by the viewer. Designers engaged in a design task see things within their work and the world around them that help them develop ideas. For example, a designer looks at a sketch, points to an element and makes a judgement about it. Where did this judgement come from?

This work suggests a model of interpretation through pull from expectations and push to a new situation when pull does not work. In this way a designer maintains a balance between a stable world (seeing what they expect to see) and a changing world (bringing concepts from outside the situation into the design conversation). In this paper two implementations have been discussed. In one a randomly generated representation is interpreted 'as' something. Different expectations of the system led to different interpretations. In the second system the initial design ideas are developed by using the ideas in creating an external representation and then interpreting the result. This leads to concepts

being brought into the design task that were not previously being considered by the designer, providing a possible explanation for the observation of this phenomenon in designers. The work starts with the observation that designers construct an interpretation from their expectations and considers the way that this affects the design conversation. It can be seen as a contribution towards understanding the relationships in the loop seen in Figure 9, trying to get at this overarching question: how do designers see?



Figure 9. Construction of an interpretation from expectations as a part of a loop involving knowledge formed through experience

Endnotes

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THE GARDENS REVISITED

The link between technology, meaning and logic?

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Abstract. The objective of this paper is to compare the computational concepts present in three books published by Mitchell between 1987 and 1990: *The art of computer-graphics programming* (1987), which has Robin Liggett and Thomas Kvan as co-authors, *The logic of architecture* (1990), probably his most influential work, and *The poetics of gardens* (1988), which has Charles Moore and William Turnbull as co-authors. By looking at the concepts that are presented in the three books and establishing a comparison between them, we expect to show that *The poetics of Gardens* should not be seen as a detour from Mitchell's line of research, but rather as a key piece for understanding the relationship between technology, meaning and logic in his very coherent body of work.

Keywords. Computational design concepts; technology; meaning; logic.

Introduction

The objective of this paper is to identify and inter-relate the computational concepts that are present in three books published by late Professor William Mitchell (two of them in collaboration with other authors) between 1987 and 1990. Two of these books are categorized in the field of computational design: *The Art of Computer-graphics Programming: A Structured Introduction for Architects and Designers* (1987), which has Robin Liggett and Thomas Kvan as co-authors, and *The Logic of Architecture: Design, Computation and Cognition* (1990), probably his most influential work. Between them, Mitchell pub-

lished a book that is usually found in a different section of the library: *The poetics of gardens* (1988), which has Charles Moore and William Turnbull as co-authors. By looking at the concepts that are presented in the later book and establishing a comparison with the two other works cited above, we expect to show that *The Poetics of Gardens* should not be seen as a detour from Mitchell's path on computational design, but rather as a key piece for understanding the relationship between meaning and logic in his very coherent body of work.

The art of computer graphics programming

The Art of Computer-graphics Programming is much more than a Pascal programming manual. In the Preface, Mitchell, Liggett and Kvan deliberately affirm that they "are at least as concerned here with issues of design theory and visual aesthetics as we are with computer technology" (p. vii). The book introduces programming techniques along with computational design concepts, through a number of shape generation concepts that can be implemented in Pascal (as in any other computer language): variables that can take different values, thus defining parametric shapes; symmetry and repetition, which create different composition from the same vocabulary; conditionals, which lead to environment-dependent solutions; encapsulation of shapes, which creates hierarchic structures; and finally, transformation operations, which carry objects from one state to another. The code examples and exercises always establish a relationship to existing architectural examples, validating the concepts presented as actual architectural design generation strategies.

The first part of the book, "Introduction to the Medium", presents information about hardware and software - which was also the subject of Mitchell's previous book, *Computer-Aided Architectural Design*, from 1977 - as well as computer-graphic principles - which would be more developed in Mitchell's book *The Reconfigured Eye: Visual Truth in the Post-Photographic Era*, from 1992. In Part 2, "Elementary Graphics Program", after a brief introduction to Pascal syntax basics, the authors start introducing computational design concepts along with programming techniques.

Chapter 8, "Graphic Vocabularies", introduces the "distinction between the *essential* and *accidental* properties of an object" (p. 167), i.e., between the general description of an object (its *type*) and its actual instantiation. The same chapter describes the "Parameterization of Graphic Elements" (p. 166), including a discussion about ranges of parameters, and the degrees of freedom of a parameterized element. The authors illustrate the fact that the same element may look different, depending on the parameters used in its instantiation, with a grove of trees. The chapter ends with a section called "Defining vocabularies

of graphic elements”.

Chapter 9, “Repetition”, introduces “Principles of regular composition” (p. 201), and proceeds with the “Use of Control Structures to Express Compositional Rules” (p. 202), which means looping through code with statements such as For/Next, While/Do and Repeat/Until. This chapter ends with a discussion about generate-and-test-procedures.

Chapter 11, “Conditionals”, presents structures that allows “to vary conditionally, according to context” (p. 273): If/Then/Else and Boolean variables. This concept is exemplified by many design situations, such as choosing among many design alternatives (state-action diagrams), exterior and interior conditions, conditional insertion of architectural elements to generate rhythms, and generate-and-test-procedures:

“Sometimes the designer knows the conditions that an instance of some design element must satisfy, but does not know the parameter values that will generate a satisfactory instance. The problem, then, is to find these parameter values... There are often formulas that can be evaluated to yield the required value directly. In other cases, however, there is no alternative to engaging in a trial-and-error process of generating candidate sets of parameter values for consideration and testing these for compliance with the conditions” (p. 312).

Chapter 12, “Hierarchical structures”, shows how to create subsystems and spatial relations by specifying “the relation between its constituent vocabulary elements” (p. 324). It also introduces the concepts of recursion and recursive subdivision. Finally, Chapter 14, “Transformations”, introduce Euclidean operations and show how to combine them with hierarchical structures, parameters and loops to generate symmetries:

“When transformation operators are applied within loops, symmetrical patterns result. The graphic element to which they are applied becomes the repeating element of the pattern, and different types of symmetry result from using different combinations of transformation operators” (p. 441).

The final part of the book, again very technical, discusses graphic packages for 2D and 3D-modeling, and for rendering still images and animations.

The Poetics of Gardens

The Poetics of Gardens could be seen simply as a travel book for garden lovers. The authors have certainly had a great time traveling around the world to visit the more than forty gardens described. It could also be seen as a simple garden design catalogue, in which gardens are grouped under certain categories. However, a careful reading reveals that the book includes many cognitive aspects of the design process that are seldom addressed in landscape design books. More than that, it establishes an unprecedented relationship between design operations and meaning: Moore, Mitchell and Turnbull say that their “concern is with the ways that places are given special meaning through actions and rituals” (p. vii).

The first part of the book (Chapters 1 and 2) describes the main ingredients (or vocabulary) for creating gardens, both tangible (topography, enclosing, roofing, connecting, watering, warming, cooling, lighting, scenting, furnishing, etc.) and intangible (the *genius loci*, *shan* and *shui*, God and Cain, memory and expectation, naming and meaning).

In the second part of the book (Chapter 3) a series of existing gardens from all over the world are presented and analyzed, grouped under the following categories: settings, collections, peregrinations and patterns. This categorization is completely different from typical landscape design books, in which examples are usually grouped by climate (such as tropical, Mediterranean, temperate, arid, etc.), function (residential, public, recreational, etc.) or scale (private house, housing development, urban square, park, etc.). The categories proposed allow interpreting gardens according to the cognitive aspects of the design process, which are also present in computational thinking.

The authors start Chapter 3 by saying that “gardens are rhetorical landscapes” that can be “read for content”, and that it is possible to “analyze [a garden’s] devices of structure and figure and trope” in the same way that we analyze a literary composition (p. 49). In other words, the reference to the organization principles of visual compositions is explicit in the book, and it is possible to infer that the categories proposed are related to cognitive strategies in design and computation, such as shown in Table 1.

Table 1: Relationship between *The Poetics of Gardens*'s categories, cognitive aspects of the design process and computer-programming techniques

Garden categorieS	Cognitive aspects of the design process	Computer-programming techniques
Settings	Visual compositions	Order of data in sets, data structure
Collections	Vocabulary of shapes	Mathematical sets
Peregrinations	Steps or procedures in the design process	Procedural programming
Patterns	Repetition according to rules, symmetry, recursion	Loop, recursive functions, parameters

The relationship with computation is probably more explicit in the Pattern Gardens section of the book. The authors start by saying that these gardens “hold us ... with their symmetries and repetitions and variations and completions” (p. 158). Persian gardens of the Mughul emperors from different periods are used to introduce the concepts of symmetry and recursion. Some of the gardens described here are the same as those that had been used by Stiny and Mitchell (1980) as the corpus of analysis to develop “The grammar of paradise”. The examples presented in this section show a progressive level of complexity. When describing the Alhambra, the authors say that

“The compositional message of the Alhambra, surely, is that intricacy is more satisfying if built in order, even simplicity, and that simplicity’s pleasures can comfortably include the dazzlingly intricate” (p. 195).

The final chapter of the book (Chapter 4) explicitly deals with the design process, through a series of examples: a courtyard, a front yard, a backyard, a side yard and a graveyard. The design process is literally described as a conversation between different references from the past, which, translated to the cognitive sciences jargon, is the same as affirming that design is a *model-based reasoning* activity.

The Logic of Architecture

Mitchell’s *The Logic of Architecture* is a much more audacious work, aiming to establish the theoretical bases of *computer-aided architectural design* and to establish a computational theory of design. With Louis Sullivan’s maxim “form follows function” as its starting point, the book is divided in three main parts, each of them defining one of the words in the famous phrase. Thus,

“form” is defined in terms of vocabularies and in terms of ways of organizing elements, such as symmetries, proportions and repetitions. Next, “follow”, i.e., action, is defined in terms of design reasoning, axioms, rules, and inference. Finally, “function” is defined in its physical, social and symbolic dimensions, and meaning is explicitly presented as one of the expected functions of a building.

Like the previous ones, this book is about the cognitive processes that take place during the design activity, and Mitchell explicitly proposes, in the Preface, to “elucidate the structure of design reasoning” (p. ix). Flemming (1992), referring to the book as a “treatise”, clearly defines its objectives:

“The general idea underlying Mitchell’s treatment ... is that of design as computation, in which computation is not to be confused with number-crunching, but is to be understood in the general sense in which the term is employed in computer science, namely, as an operation or a sequence of operations performed on some symbolic representation” (Flemming, 1992, p. 105).

Computational concepts applied to formal compositions are presented mainly in Chapters 2 “Architectural form”, which includes a section called “Rhythm, proportion and symmetry”, 3 “Design worlds”, 6 “Types and vocabularies” and 7 “Design operations”. The concepts of vocabularies, types, parameters, symmetry, repetition, variation, combination, transformation, conditions and rules are thus reintroduced here, but within a much more formal framework, with references to Artificial Intelligence and Computer Science theories.

As stated by Flemming (1992), the book is not likely to be well-understood by everyone: the concepts presented are extremely abstract and it relies heavily on examples taken from classical architecture, “with its known regularities and conventions” (p. 105). In other words, *The Logic of Architecture* is a book for initiated researchers with at least some background in computation.

Comparison

In an implicit way, *The Poetics of Gardens* includes most of the computational design concepts that had been previously introduced in *The Art of Computer-graphics Programming* and that would be further developed in *The Logic of Architecture*. Table 2 shows a summary of the main concepts that are presented in each book.

Table 2. Computational concepts presented in each book

The Art of Computer-graphics programming	The Poetics of Gardens	The Logic of Architecture
parameters symmetry repetition/recursion conditionals hierarchy of parts transformations	elements (vocabulary) garden types (categories) settings - metaphors collections - nouns peregrinations - verbs patterns – verses repetition variation combination symmetries	descriptive methods architectural form rhythm, proportion, symmetry design worlds points, lines, planes, volumes critic languages design reasoning types/vocabularies design operations transformation combination substitution architectural languages function

It is possible to say that the three books are inter-related and complement each other. Yet, their character and target public are completely different. While *The Art of Computer-graphics Programming* can be considered a technical book, *The Logic of Architecture* is in the opposite end, and can be seen as a philosophical treatise. *The Poetics of Gardens* is in between, not as technical but also not as philosophical. While *The Art of Computer-graphics Programming* can be easily read by both engineers and computer scientists (on top of architects), *The Logic of Architecture* might be of interest to both philosophers and logicians (maybe even more than to architects). *The Poetics of Gardens*, on the other hand, is mostly interesting for architects and landscape architects, but that is probably because the computational design community are still to discover this book.

It is interesting to note how the same concepts are presented in each of the books in a slightly different way. For example, the concept of essential and accidental properties was introduced in *The Art of Computer-graphics Programming* and further refined in *The Logic of Architecture*. However, the concept was also used in *The Poetics of Gardens*, to explain how the *chahar bagh* pattern could be instantiated in different ways. All the different *chahar bagh* gardens were based on the same prototypical idea, but each of them introduced particular characteristics (accidental properties) depending on their physical extent, the availability of water, the topography and so on.

Similarly, the concept of parameters is initially introduced in *The Art of Computer-graphics Programming* and further developed in *The Logic of*

Architecture (Chapter 7, Design Operations, section Instantiating Primitives). In *The Poetics of Gardens*, the different patios in the Alhambra are presented as parametric variations of the same model, formed by a central open space with a fountain and four vaulted spaces around it. Another example of how parameters can receive different values depending on the designer's intents is William Kent's planting scheme for Rousham, in which the landscape designer uses a variation of tree heights to create different perspectives to the river along the way:

“[Kent] indicated deliberate yet carefully controlled variations of the characteristics of the woods along the paths, from high tree forests to underwood and tall shrubs” (p. 129).

Types and vocabularies are also introduced in *The Art of Computer-graphics Programming* and further developed in *The Logic of Architecture*, in which Mitchell states that architectural styles can be defined in terms of their vocabularies of shapes. In *The Poetics of Gardens*, the authors describe, in Chapter 2 - The designer's place, an example of a clear definition of a vocabulary: the eleven elements of a Japanese Garden.

The concepts of repetition and recursion, again introduced in *The Art of Computer-graphics Programming*, are associated, in *The Logic*, to symmetry and rhythm “in most buildings, there is a repetition of elements, such as columns” (p. 27, Chapter 2 - Architectural form; section 3 - Rhythm, proportion and symmetry). Recursion is seen as one of the possible design operations. In *The Poetics of Gardens* recursion is illustrated and given meaning by different Mughul Garden designs. The gardens of the tomb of I'timad-ud-Dula, for example, don't need the same level of recursion as the bigger tombs of the emperors. Being smaller, the canals along the main axes and the perimeter suffice for irrigating the ground.

The Poetics of Gardens is a link between *The Art of Computer-graphics Programming* and *The Logic of Architecture*. Theory and technology alone are like water and oil; they do not mix easily. The architect must provide the context to weave them together meaningfully. In this case, the context was landscape design.

Discussion

Computational approaches have often been criticized for being unable to handle subjective dimensions of design, such as meaning. Fleisher, for example, has suggested that shape grammars fail to handle meaning because in the traditional design process “one sketches to explore lexicon and semantics. Neither words nor meanings are prior. They are assigned on trial, locally

and globally.” Meaning cannot be “entirely prescribed or anticipated” (p. 224). Still according to him, “Grammars for exploring [shapes] would invent structure and meaning simultaneously, consistently.” (p. 224), but he believes that “geometry is the only part of the architectural argument that is computable” (p. 225).

The Poetics of Gardens shows that meaning in design can be the result of the systematic application of shape rules through a series of built examples. In the design of gardens, formal composition responds to symbolic requirements in addition to pragmatic issues. For instance, in Persian gardens, symmetry evolves with the type of political power held by the emperor. Rules, thus, can encapsulate meaning.

In summary, the analysis of *The Poetics of Gardens* allows concluding that:

- The cognitive processes that take place during the development of a design project include many computational operations, both for establishing the visual composition and for defining its meaning;
- The book is about the computational and cognitive aspects of the design process, rather than simply a catalogue of gardens;
- Among the three books analyzed, it is the less subject to obsolescence, because it discusses very fundamental concepts of design, without any explicit reference to technology.

After concluding this series of books about **computational concepts in design**, which can be seen as a trilogy, Mitchell published many other titles, with colleagues or by himself, always related to design, technology and meaning. Some of his other books can also be grouped together by theme, such as:

Applications of the new technologies in the design process

- The Electronic Design Studio: Architectural Knowledge and Media in the Computer Era (McCullough, Malcolm, William J. Mitchell and Patrick Purcell, eds., 1990)
- The Reconfigured Eye: Visual Truth in the Post-Photographic (Mitchell, William J., 1994)
- Digital Design Media: A Handbook for Architects and Design Professionals (Mitchell, William J. and Malcolm McCullough, 1996)

Impacts of connectivity in the urban space

- City of Bits: Space, Place, and the Infobahn (Mitchell, William J., 1995)
- E-topia: Urban Life, Jim—But Not as We Know It (Mitchell, William J., 1999)

- Me++: The Cyborg Self and the Networked City (Mitchell, William J., 2003).

Most of these books have been translated to other languages. E-topia, for example, was translated to seven languages. On top of the books, Mitchell published hundreds of papers in journals, magazines, newspapers and conference proceedings. This shows the relevance of his words and at the same time the size of the legacy that he left us.

Revisiting this legacy, for example by publishing commented translations, can bring up new interesting discussions. The Portuguese version of *The Logic of Architecture* (UNICAMP Press, 2009) includes a glossary about first order logic and artificial intelligence concepts, and the Portuguese version of *The Poetics of Gardens* (UNICAMP Press, scheduled for 2011), will have hundreds of footnotes for the younger readers, who are not so knowledgeable about British literature. One of the authors of the present paper plans to translate *The Art of Computer-graphics Programming*, adapting the codes to a more contemporary programming language. The new book will probably be very useful as a programming manual for present days architecture students.

Even though Mitchell is not with us any more – he is probably enjoying the most beautiful garden of all at this moment, with the other authors of *The Poetics of Gardens* - we believe that the concepts present in his books still have a great potential for teaching design and computation, and thus should continue to be explored in many ways.

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ARCHITECTURAL SPACE INFORMATION SCALE

A new way of understanding architectural space

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Abstract. This paper presents a proposal for digitalizing architectural space. For this aim, the analysis of space properties in terms of an information scale is suggested as a new way of understanding architectural space. Information scale in this paper is a new concept integrating the body scale, behaviour scale and time scale in traditional conceptions of space. Through the process of information transfer, forms, behaviour, history, design, experience, evaluation etc. in architectural space are integrated into a well-arranged and operational approach. BIM plus SIM (Space Information Model) thus constitutes an integral architectural information model.

Keywords. Space information property; space information scale; Space Information Model.

1. Space Information Model

Through BIM (Building Information Model), architectural digitalization has developed to offer a new perspective and understanding of architecture. In contrast to the digitalization of entity objects, the digitalization of space remains a question. From the perspective of BIM, the establishment of SIM (Space Information Model) becomes a natural choice. We try to find a new answer to the understanding of the traditional topic in the architecture—space, from the perspective of digitalization.

1.1 PRESENTATION OF THE CONCEPT

A main way of solving problems in architectural design is information processing theory. Information provides the basis for the design and

understanding, and it determines and influences problem solution and decision making in various stages. The analysis process is actually an information processing process, during which the flow of information becomes an effective way of understanding.

Since architectural design is a massive task subjected to various factors, architects tend to adopt a citation-based and synthetic way of thinking, instead of an inductive and analytical one. This synthetic way of thinking results in the rarity of inductive and analytical ways of designing. Their ways must be more comprehensive and can't lose in mechanization, so they should be more system-oriented, which is not achievable by any linear procedure. Therefore, different from the deductive reasoning familiar to scientists and engineers, the architectural reasoning is additive. Analytical deduction works through certain independent factors, based on which an entity is established; while additive and synthetic reasoning takes the whole complex entity into consideration, and tries to coordinate different elements perfectly, so as to realize the greatest value and truth of the entity. Integrity is the essence and feature of architecture and the Space Information Model will give full play to integrity as a medium.

1.2 THE CONCEPT OF "INFORMATION"

So far there is no precise definition of "information". Its connotation is multifaceted and cannot be defined from the perspective of individual disciplines. A new understanding of information can only be obtained according to the characteristics of different disciplines.

Williams (1995:38), once depicting the gene as a package of information, pointed out that DNA is the carrier of the gene, not the gene itself. This understanding is comparable to that of space in architecture. The relation between space and space information can be put this way: space is the carrier of information, not the information itself.

Table 1: Understanding of information in philosophy

Essential Property	Information is an ordered sequence of matter and energy movement in the external world, and is the self-organizing system's active reflection and reorganization of the sequence.
Purpose	Philosophy of information can explain and guide the purposeful construction of knowledge, and can deal with the conceptual basis systematically in modern society. It enables people to understand the world and construct it responsibly, which is a new stage of the semanticised "being".

Function	Information is one of the most unprecedentedly powerful word in philosophy. This is because it can be counted on whenever a full understanding or a consistent explanation of some events can't be achieved. In philosophy, this means that any question can in fact be re-formulated with information terms. This semantic power is a great advantage of the philosophy of information as the methodology.

Table 1 shows that information is very powerful, helping to render an explanation of things people have not yet fully understood. This matches the fuzziness of architectural space, a complicated object. It's effective to present space through space information properties.

1.3 SPACE INFORMATION PROPERTY DEFINED

Just as "mass" is used for the uniform measurement of different substances and "energy" for the different movement of metrics, we can now use "information property" for the measurement of requirements and properties of different things. Information properties describe the different degrees in organization and high/low order of things. Space itself is multi-dimensional and is more than just visual. The space we recognize is never the whole space, and different perspectives and approaches are only able to recognize one of its sides, or to convey certain information. Information scale provides a clear understanding direction, and when people's needs and the information provided by the space fit together, space quality gets realized. Bill Schiller used "space syntax" to analyze the variables that control buildings and tried to establish the laws between spatial fabric and the built environment. Here "variable" actually is also a form of space information property.

Overall, space information property is the reflection of the possible existing state relative to the subject. Space information property is not space itself, but the possible state of space, and is a representation of the causal linkage between the interaction and correlation universally existing amongst space elements.

1.4 SPACE INFORMATION SYSTEM DEFINED

Space information properties must be organized in a certain systemic way before they can be understood and used, and this systemic way is provided by the Space Information System (SIM), a model that presents space information properties proposed in this paper. It is not a simple collection of space information properties, but has a complex logical structure. Understanding from different angles lead to different points, even with the same space object

or element, leading to separated flow of information, which will continue to occur. After synthesis, a fairly comprehensive and valuable information hologram will be formed. Therefore, the Space Information System is a complex, redundant network structure, rather than a linear one.

Digitalization provides a basis and possibility for the tendency to scientise architecture. On this basis, architectural design can be conducted on scientific principles structurally similar to that of theoretical physicists and biologists. Under the framework of BIM, a model provides a single, integral, consistent and logical architectural information database. The technological core of BIM is a database composed of a computer 3-D model, which not only includes architects' design information, but also accommodates the information of the whole process from design to use, even to the end of the use life circle. In addition, all kinds of information is restored in the 3-D model database, capable of providing consistent and real-time information of the scope, progress and costs of the project design. This information is complete, reliable and fully coordinated.

The technical requirements brought about by the complex problems in architectural design have already gone beyond the architects who rely on their "feeling" to tackle problems. It's more so with building space, feeling being replaced by optimization and experience by simulation testing. This is an inevitable trend of architectural design in the digital age. To meet the demand of behavioural needs is the basis for the existence and realization of space. This is how SIM and BIM are different. The purpose of BIM is to achieve the building, while that of SIM is to realize behaviour. Therefore, the establishment of SIM must be around the relationship between behaviour and space.

2. Architectural understanding of behaviour-space relationship

Architecture is the study of the built space designed to meet different behavioural needs, and of the theories of and approaches to architectural environment design. Space in architecture is artificial aimed to meet certain people's behavioural needs. We get access to space by operating entities, and space exerts its effect on behaviour via space information transfer, and ultimately realizes its meaning.

2.1 SUBJECTIVITY OF SPACE

The dominant position of space in architecture has been gradually blurred, and public space is more of an end than an aim. Space is never empty. It often contains some kind of "meaning". How can the "meaning" be conveyed

to people? Space information provides the channel to reveal and connect everything in it. Information is a philosophical category denoting existence indirectly, and it is a reflection of physical existence (direct existence) and of states. By the existence of space information, space realizes its subjectivity.

The main body of space is men rather than space itself, since space just provides a physical and location basis for the occurrence of human behaviour. In built space, people realize activities and behaviour. In defining space, artificial environment and human behaviour are the main points. From this point, space can be defined as the artificial environment for people's life and activities. Social life and activities get realized through human behaviour, and human behaviour is guided and limited by the architectural space and gets influenced via the transfer of certain information.

2.2 REALIZATION OF ARCHITECTURAL SPACE AS A GOAL

After determining the dominant position of space, the first question is the realization of space quality. It is based on the response to human physical and behavioural needs. There are two processes: needs and response. When the two processes fit together, space quality gets realized, and the tie between them is space information. Realization of every quality space corresponds to a complex process of information transfer. In terms of the relationship between man and space, man has needs and space responds to them. These needs, in the process of realization, take different forms, like space information transfer, knowledge, use, response, occurrence, backflow, etc. Such a complex process of information transfer happens in every built space, and it realizes space quality.

2.3 REALIZATION OF ARCHITECTURAL SPACE IN TERMS OF INFORMATION

Against the background of the big advancement of digitalization, SIM serves as a technical support to design, helping designers and decision makers to develop a clearer goal before designing, to command a more effective control in designing and to conduct a more accurate analysis and evaluation after designing, so that the whole process of space realization can be integrated in a real sense and the design runs through deep into the whole process.

From the perspective of space information, the realization of space can be re-presented in the way below in Table 2.

Table 2: realization of space in terms of information

Process	Investigation	Design	Use	Evaluation
information scale	obtaining space information	utilizing space information	the response to the information conveyed by space	Smoothness of information transfer Response to the information information redundancy rate

3. The information scale of architectural space

To establish the Space Information Model, the forms of space information properties must be identified, which has to be based on the establishment of information scale. Space information properties cannot be revealed without the measurement of space information scale.

3.1 KNOWLEDGE AND MEASUREMENT OF SPACE INFORMATION

There are two accesses to space information: knowledge and measurement. Basically knowledge involves information processing. "Information" here actually is what we mean by "knowledge". One of the important features of cognitive science lies in the study of information processing, but a fairly large amount of information is beyond our knowledge, that is to say, it has to be obtained through other channels. Some properties of architectural space are measurable and well-established, such as size, materials, etc. As to the unmeasurable, they can only be understood and explained via concept types. The two accesses to space information is presented in Table 3.

Table 3: Two accesses to space information

Accesses	Knowledge	Measurement
Information point of view	subjective	objective
Manifestation	diagram	quantification
Information forms	relations, composition	factors, attributes
Information attributes	relative	absolute

The greatest difficulty with SIM is the lack of any specific and tangible system equipment to process information effectively, but can only rely on designers' use and judgment. SIM focuses on training people, while the role of technology is only to provide a basic framework of support and understanding. From another point of view, this is where human subjectivity comes in.

Rule of thumb and law of order show how information is organized. A model is an abstract simplification of the real world. In daily life, psychological

models, diagrams, texts or other models of reality are often used, consciously or unconsciously, as analysis tools. The appearance of computers has greatly enhanced people's ability to simulate the external world and the development of computer technology makes it possible to consider more complex models.

3.2 THREE SCALES OF SPACE

Scale in general refers to the size of an object, and is sometimes used to represent the standard of doing things or looking at things. There are three established space scales in architecture, namely, body scale, behavioral scale and time scale.

Architectural scale generally denotes the proportional relationship between the whole building and local entities and the people or objects they are familiar with as well as the feelings people get in this relationship. In architectural design, a person or some invariant elements related to body movements, such as a door, steps or railing, are often taken as a reference. By comparing to them, people get a certain sense of scale. This is what a typical "body scale" is. Behavior scale indicates a spatial relationship based on behavior, and the standard for comparison is the occurrence of behavior in space. It reflects the constraints and motivation of space to behavior. Time scale is the time dimension in space, the standard being the start, development and end of behavior in time dimension. These three scales are shown in Table 4.

Table 4: Three established scales in architecture

Scales	Behavior Scale	Body Scale	Time Scale
Scope	space-behavior	space-body	space-time
Objects	behavior mechanism the influence of space structure	body perception of space physical constraints on behavior	time point, time quantum, frequen- cy and sequence of behavior
Information types	behavior property	physical property	time property

3.3 INFORMATION SCALE

These three scales have their own scope of application and objects of evaluation, but can hardly cover the whole space. They have to be integrated before we have a comprehensive and systematical understanding of space, and this is where information scale comes in. Space types are, to some degree, different slices of space information, and slicing from different angles results in different types, reflecting different transects of space.

For example, how can a point be determined? Two coordinates will do in a plane coordinate system, but three vector coordinates are needed in the three-dimensional coordinate system. SIM is three-dimensional and complex, and the location of one information point needs the joint determination of the three coordinates of scales. Hence, the space information scale provides a standard to measure space information properties that makes it possible to systemically analyze and measure space information properties.

Untested and closed knowledge systems will eventually decline or fall into dogmatism, since science is open. Buildings are no longer realized by any forms of empiricism or experimental validation. The idea of space information integrates a number of diverse disciplines, making space an object which can be discussed and evaluated, offering architects and architecture students a language that is understandable and applicable.

3.4 FORMS OF SIM

The information provided by space is the premise of behavior and space itself is where behavior occurs, so the discussion of space information properties has to start from the space-behavior interaction. Hence basic clues of space information properties are as outlined in Table 5:

Table 5: Three clues of space information system

Three Clues of Space Information System			
Relationships	Space-body	Space-behavior	Space-time
Goals	physical comfort of environment	appropriateness of behavior	order of behavior
Stages	observation cognition design	use design evaluation	current past

Space can be defined in an “object description+ properties” way, like the way of describing objects under BIM. Take the Wall System of Autodesk Revit 2010 as an example. An object is defined as object=object description + type properties + element properties. What if this way of defining in BIM is mapped to space? Considering the three clues of space information properties, we get the following composition of space information model, or the forms of space information properties, as shown in Table 6.

Table 6: The presentation forms of space information

	Clues		Physical Comfort of space	Appropriateness of behavior in space	Order of behavior in Space
Space Information=	Space	+	Physical Property	Behavioral Property	Time Property
	Description Type properties (room, corridor, staircase, lobby.....)		Geometry (<i>sizes, parameters</i>) Substance (<i>material, techniques, properties</i>) Stages (<i>manufacture, construction, design, evaluation</i>) Body perception (<i>sound, light, heat</i>)	User (<i>number, quality, purpose</i>) Direction Relationship with space Spatial capacity Behavior density Behavior fullness Participation	Time point Time quantum Sequence Duration

This way of defining space is the basis of the digitalization of public space, and it provides space digitalization with an expression of parameters and properties of space. Based on this, the establishment of an integral Public Space Information Model (PSIM) becomes possible. The “object description+properties” way of defining opens a new channel to the understanding of urban public space, and makes designing more purposeful. Meanwhile, the Space Information System is open to supplement.

4. Conclusion

With the boom of architectural digitalization, the digitalization of space as the main object of architectural design becomes a top priority. The main purpose of this paper is to put forward this proposition, and based on this, to offer a new way of understanding architectural space. As a specific means to analyze space information properties, space information scale provides a new way of understanding architectural space. This method is based on science and takes space information as the medium, in order to establish a theoretical foundation for space digitalization. Information systems are characterized by their openness, and the information scale ensures gradual and orderly accumulation of new knowledge about architecture, which is different from the linear accumulation in other disciplines. This is due partially to the synthetic nature of architecture. Then, the structure and organization of the system becomes the main topic. Once the structure of knowledge and

information is determined, the goal of the following work is clear. However, space information properties cannot describe all aspects of space. That is because space digitalization is based on the knowledge and understanding of the space, which has to consistently keep up with the progress of technology, people's mode of knowledge and ways of thinking. Therefore, the proposed Space Information Model will get constantly richer and supplemented. This paper made a preliminary discussion of the structure of SIM, but does not address specific aspects of digital technology. Further studies are yet to be done.

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A IS B, DISPLACEMENT: EXPLORING LINKING PATTERNS WITHIN METAPHOR IN THE DESIGN PROCESS.

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Abstract. Design educators often apply metaphor as a teaching tool to help novice designers in their design process. Richards(1936) defines metaphor as the form “A is B”. The most important operation in metaphor is displacement—the linking process of moving A to B. Linking ideas is the key mechanism in the design process. By linking ideas, a graph-like knowledge represents the individual memories with the nodes and arcs that are the ideas and the links between ideas respectively. Such linking knowledge provides an interesting way to understand the operation of displacement within metaphor. This research applies a computational tool (called DIM) to produce a graph-like knowledge. Protocol analysis is then used to understand how designers organize ideas. The objective of this research was to explore the linking patterns of idea displacement within metaphor in the design process.

Keywords: Metaphor; displacement; linking ideas; graph-like knowledge; protocol analysis.

1. Introduction

In the early stage of design, designers often use metaphor for their design inspiration. Through the clues of linking knowledge that metaphor reveals, designers can understand the relationships between diverse ideas and design outcomes (Antoniades, 1992). Design educators often apply metaphor as a teaching tool to help novice designers in their design process (Casakin, 2006). The idea of metaphor is that two unrelated concepts link together to generate a new meaning (Lakoff, 1987). Richards (1936) defines metaphor as the form

“A is B”. A is the tenor through which we intend to understand B. B is the vehicle which helps us to understand A. The most important operation in metaphor is displacement—the linking process of moving A to B. In the process, A (tenor) and B (vehicle) can be regarded as ideas (Schön, 1963).

For example, in the case of the John F. Kennedy International Airport in New York City, the airport was used to link concepts of “flying” (as a tenor A) such as birds’ wings, aerofoil, or hydrodynamics . . . etc in order to generate an airport with a freeform roof (as a vehicle B). Therefore, displacement involves the process of linking and generation. Lai (2005) indicated that idea linking plays an important role in the generation of diverse ideas through linking designers’ memory. Such linking knowledge, which includes ideas and relationships, provides an interesting way to understand the operation of displacement within metaphor.

Furthermore, the Dynamic Idea Map (*DIM*), constructed by Lai and Chang (2005, 2006), reveals processes and reinforces image operational information. Our study used DIM as a platform along with an IE map of different ideas connected by three different linking relationships: similarity (si), contrast (cr), and contiguity (ci). Thus, ICFP, as the knowledge representation, helps construct knowledge and provides an efficient method to reveal the design ideas and the knowledge links between them. Using the keyword for the domain conceptual vocabulary of designers, Issue (*I*), which combines the descriptive Concept of the text (*C*) with the Form created by the keyword and the image (*F*), and the Preference value 1–5 of those surveyed (*P*), they constructed a database with ideas and links. DIM primarily combined case-based reasoning with the software agent operation mechanism and, through the agent communication platform (JADE) and reasoning engine (JESS) technology, produced graph-like knowledge links.

2. Displacement as the process of linking ideas

Schön (1963) points out that designers often apply metaphor to displace different ideas. This is done to solve design problems through linking their constructive knowledge in their memory. Antoniades (1990) argued that designers use the phrase “architecture is . . .” to link and generate ideas. By using the phrase effectively in the design process, designers can have creative design outcomes. But how are A and B actually displaced in the metaphor? How does the knowledge associated with object A link with the knowledge associated with object B? Only when one knows how knowledge is displaced and linked by the designer is the metaphor process slowly revealed.

2.1. LINKING KNOWLEDGE IN DESIGN

Oxman's research (2004) showed that by not measuring the quantity of knowledge gained, but by knowing where to find it, we can know which specific kind of knowledge to apply in a particular situation, and how to use it when needed. Norman (1988) believes that during the search the designer obtains the best solution by mapping, relating, and deciding between design-related objectives and policies through special limiting factors.

The issues with the metaphor displacement process during design are: 1) how the relation between A and B is found through this searching, and 2) how the conceptual mapping process of the designer is revealed by their linkage.

2.2. LINKING OPERATION WITHIN DISPLACEMENT

A metaphor is the significant displacement between A and B (Ricoeur, 1977). Black (1962) believed that a metaphor is the similarity between the creation of A and B where A and B are additionally linked at different levels and are combined to produce significant variation. Way (1991) showed that in the displacement of A to B, the level of A will gradually link with the field of B through the re-description of the attributes of A and B, gradually blurring the differences between the two.

For the field of architectural design, the designer often deconstructs a design into architectural elements (Mitchell, 1990), and builds architectural design knowledge through the relationship between the element symbols and the elements themselves. Liao (2009) also mentions that designers search for meaningful keywords or images as concepts of metaphor, and then transform the concepts to meet their design needs. Based on the rules of metaphor (Ricoeur, 1977), the concepts can be classified into four types: *property*, *form*, *function*, and *structure*. They provide our understanding of the sources of metaphor to link and generate ideas. According to the above theory, A and B should possess these four metaphor rules if they are to be considered displaceable. The description is as follows:

- *property*: The classifications and associations of metaphor object A and the architectural characteristics of metaphor object B.
- *form*: The form of metaphor object A and the architectural appearance of object B.
- *function*: The special functions of metaphor object A and the architectural function or program of object B.
- *structure*: The composed structure of object A and the architectural structure of metaphor object B. sign Research in Asia

For example, we can use the four rules of metaphor to analyze the Beijing

Olympic National Aquatics Centre, or the “Water Cube” (designed by PTW, 2008). For A, the water in the swimming pool was deconstructed into some properties. The molecular form of water are constantly linked to bubbles, so its form is a bubble and its function is the functions associated with bubbles, such as isolated temperature and a high load capacity. The structure is the crowded structure of the water molecule. Architecturally, the bubble form changed into the architectural appearance, the bubble functions transformed into the temperature barrier of the outer wall, and the crowded molecular structure of water became the architectural model. Figure 1 shows the metaphor design process analysis for the Beijing National Aquatics Centre.

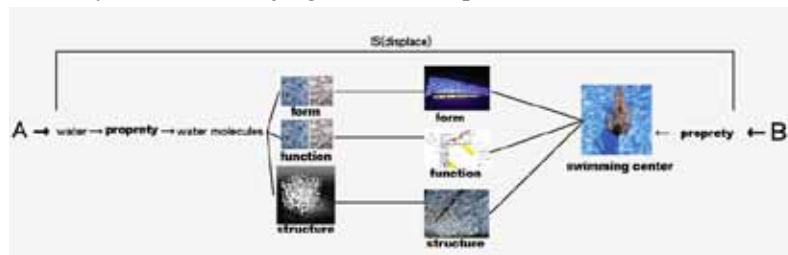


Figure 1. The metaphor displacement of the Beijing National Aquatics Centre.

2.3. SUMMARY

Previous studies have emphasized on the use of metaphor for generating design outcomes in the process of displacing A to B, but lack more detailed descriptions of the knowledge linking process. Oxman (2004) claims that only through a concept structure of the entire knowledge linking network can we understand the analogy reasoning pattern in the thinking process. For this reason, the objective of this research was to explore these linking patterns by discovering the displacement process used by designers.

To find the underlying structure of displacement via mapping the linking behaviour, a mapping mechanism and an observation method over the experiment are needed. The mapping mechanism should generate a graph-like knowledge structure which composes vast amount of ideas and their links (the relationships between puzzle pieces). Thus DIM mentioned above, which can generate the graph-like knowledge (called idea map) of links and nodes, can support the mapping mechanism.

Based on the protocol analysis methodology, through the process of encoding, recording, and data analysis, a design's behaviour can be comprehended. This research applies think aloud and conceptual sketches to understand design operation of displacing ideas.

3. Design experiment

To explore the linking operation of displacement, this research applied the DIM as a supporting tool to conduct a design experiment.

The purpose is to understand the linking relationships among four types of concepts (property, form, function, and structure). Tenor A can be set to the attribute issue (I). Four types of metaphor rules can be set to the attribute concept (C) (Figure2). Three types of linking relationships (si, ci, and cr) allow us to explore the relationships between A and B.

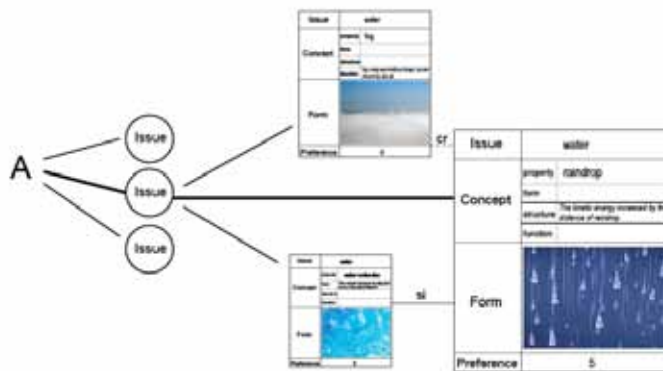


Figure2. The relationship between A and ICFP (Issue, Concept, Form, and Preference).

It is hoped that this experiment will help novice students to enhance their own concepts and ideas in developing design solutions and to help them overcome their lack of knowledge and experience. The participants in the design experiment were ten third year architecture studio students. Utilizing the tourist information station on the Danshui waterfront as the topic, this study observed how the designers used this tenor (A) as metaphor to apply the property, form, function, and structure as Concept. By doing this we can understand the pattern of how the knowledge was then displaced through displacing the links from si, ci, and cr to the vehicle (B). The students' design operation of displacement was recorded and interpreted via protocol analysis.

The main elements of this experiment are described below:

- Participants: Ten third year architecture college students who have undergone basic architecture training and are familiar with DIM and design within metaphor.
- Design Task: So that the experiment could observe directly the thinking transition during the design process, we took as a topic the simple function of a design project of an information station for tourists located on the Danshui River. Being the displaced vehicle B, because the site and rivers are closely

related, the subject fixed water as the primary metaphor issue, meaning tenor A.

- Process: The test ran for 75 minutes. The participant carried out DIM experiment warm-up and operation for 15 minutes prior to the test. During the last 30 minutes, he/she was required to draft his/her conceptual sketches whilst undergoing thinking aloud. The whole process was videotaped.

4. Analysis and observations

After the test described above, 15 design ideas were created by every participant within a 30 minute period. From the 15 ICFP, each participant again found an object that could be displaced by A, and carried out link displacement with the B displacement object. In this way, patterns were observed.

4.1. ANALYSIS

This research fixed the information station as metaphor displacement object B, set the design issue (I) as the water (tenor A), and separated it conceptually into different properties. Providing property image F as a reference, students first chose an ICFP according to their Preference and then began to construct a knowledge framework about water from the form, function, and structure in the Concept. After using si, cr, and ci to link the corresponding architectural function, structure, and form, students recreated the concept map and derived the design. The entire experiment process is shown in Table 1.

Table 1. Metaphor displacement process.

	A	is (displacement)				B
1	① water	property	→	① → ② → ③	form function structure	property
2		property	→	① → ② → ③	form function structure	property
3		property	→	① → ② → ③	form function structure	property
4		property	→	① → ② → ③	form function structure	property
5		property	→	① → ② → ③	form function structure	property
6		property	→	① → ② → ③	form function structure	property
7		property	→	① → ② → ③	form function structure	property
8		property	→	① → ② → ③	form function structure	property
9		property	→	① → ② → ③	form function structure	property
10		property	→	① → ② → ③	form function structure	property
After translati						information station

was approximately one displacement process for ten participants' metaphor concept issues, which were created through new connections produced after recombining the four different rules. In the entire displacement design process, the rules for A is B was similar to Figure 3:



Figure 3. Linking pattern during the experiment.

The displacement design process was as follows:

Through translating protocol analysis and observing participants in the design process of displacement, we discovered that when displacement is used in the design process, the designers will first focus on the water issue of the overall metaphor, using DIM links to different properties like water molecule, bubbles, and mist. They will then search the property image F for visual references and, according to the form or structure and function deconstructed from the guiding concepts in the image, create an object displaceable by A, thereby deriving the design.

In another aspect, architectural design will also be deconstructed into different properties. Because the information station is set as the subject, participants will first consider its properties, also divided into form, structure, and function, to find an object that can be displaced by B.

The protocol analysis of two participants, code-named participants 1 and 2, are used as an example (see Table 2).

TABLE 2. Protocol analysis in the design within metaphor displacement.

Participant 1: protocol and sketch	Participant 2: protocol and sketch
Because the weather of this site is rainy, people get used to live here with <u>raindrop</u>. My concept of this design is to catch the <u>moment of raining</u>. The form of station is looks like the form of the <u>drops</u> through process become fog that is <u>without specific shape and border</u>. The structure of the station is like <u>fog contains</u> filled in bubble. The function of station is like <u>still water</u> can be <u>reflected and interactive</u>. 	My initial idea is about the <u>function</u> of information station such as collect information, rest point, gallery or it could be an iconic building. First I apply the concept of form called <u>oil-water separation</u> into the function of station. My imagination of the architectural form is like the structure of <u>bubble that flexible and movable</u> description with <u>colorful and malleability</u> form. The program of gallery (like oil) is separate the information center (like water), people are like drop that can effect the space dynamically. 

- The displacement objects of A and B will gradually link. For example, Participant 1 used the concept of oil-water separation as the function from the water issue (A). The description of oil dispersed on the water surface, unable to dissolve but instead floating became the primary concept for the program of gallery in the information station (B).
- Participant 2 used the A issue property of mist and raindrops as the displacement concept link for the form of the roof.

4.2. OBSERVATIONS: THE PATTERN OF DISPLACEMENT

The findings of this study should assist in the computing of displacement, and can help designers understand the linking pattern and knowledge construction for effective use during design processes.

The analysis of the displacement process from A to B shows that:

- More participants linked the form of A with the form of B.
- The form of A was applied most, and could be si-linked to the form of B, or ci- or cr-linked to the function and structure of B.
- If the participant started with function for the link to B, it was easier to directly displace the function of A with the function of B.
- If the participant started with structure for the link to B, it was easier to directly displace the structure of A with the structure of B.

5. Conclusion: Linking pattern of displacement

In this experiment we discovered that when the designer designs within displacement, the pattern between A and B showed that, primarily, the form, function, and structure of A tenor C corresponded with the form, function, and structure of B. The state of these corresponding relationships could be separated into four different patterns (see Figure 4).

- Pattern 1: Participants more often corresponded the form of B with the form, function, and structure of A tenor.
- Pattern 2: Participants would simultaneously si, cr, and ci link the form of A tenor C with the form, function, and structure of B.
- Pattern 3: Participants would simultaneously si, cr, and ci link the structure of A tenor C with the form, function, and structure of B.
- Pattern 4: Participants would directly si link the form of A tenor C with the form of B, the function of A tenor with the function of B, and the structure of A tenor with the structure of B.

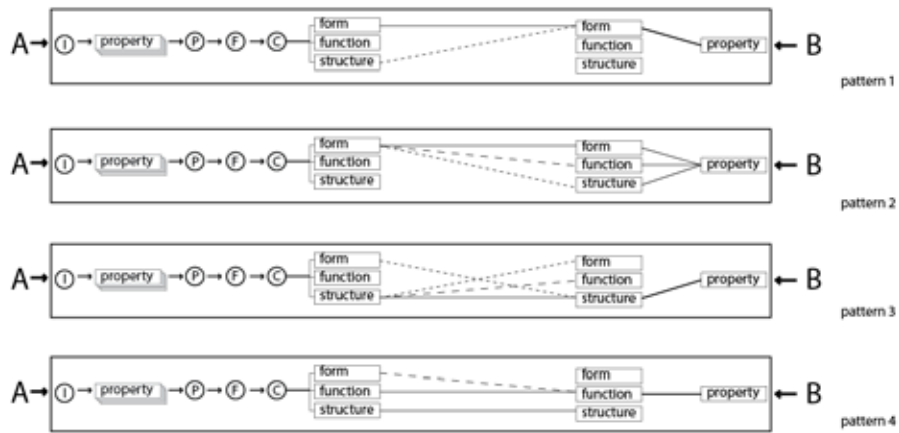


Figure 4. Linking pattern of displacement.

The experiments indicate that designers proceed in metaphor displacement by first linking characteristics of a metaphor target with itself, then derive to the sources of a completely different field. This further leads to the development of a multi-dimensioned imagination that transcends the functional requirements. The richer variety of architectural design possibilities then emerges while the connection with its characteristic of site might possibly get closer. This research has explored the linking patterns that designers apply in the displacement process. In this process, they can also develop brand new perspectives and imagination toward design. Future research will aim to conduct experiments with more participants and test the mechanisms for further applications. It is hoped that the mechanism will lead to develop a type of supporting tool for computerization and application in the field of architectural design education. Whether or not this can further be developed into a dynamic metaphor teaching game will be the focus for future research on this topic.

Acknowledgements

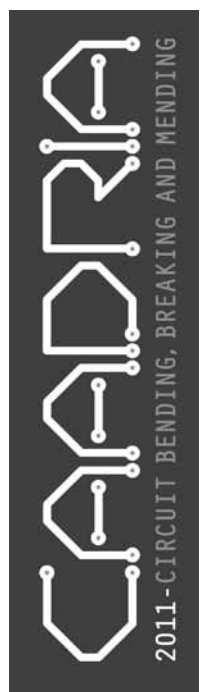
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COMPUTER SUPPORTED DESIGN COLLABORATION



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64.	Memo Externalizer: Support environment for bridging from personal ideas to group discussions in design meetings <i>Yuji Matsumoto, Yusuke Okada, Nagisa Kidosaki, Ryusuke Naka and Shigeyuki Yamaguchi</i>	677
65.	The role of collective intelligence in design: A protocol study of online design communication <i>Mercedes Paulini, Mary Lou Maher and Paul Murty</i>	687
66.	Motivation, cyberworlds and collective design <i>Kathryn Merrick, Ning Gu, Muhammad Niazi and Kamran Shafi</i>	697
67.	Colour-code models: The concept of spatial network <i>Paulina Neisch</i>	707
68.	Packing the “Chinese box”: A strategy to manage knowledge using architectural digital models <i>Simone Garagnani</i>	717

MEMO EXTERNALIZER

Support environment for bridging from personal ideas to group discussions in design meetings

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Abstract. This paper describes our development of a face-to-face design meeting environment that considers the integration of IT and architectural space. The Memo Externalizer (ME); proposed system, focus on how to externalize personal ideas in group discussions. The ME is a very simple system using lightweight technologies; web cameras which film each participant's memos and monitors which are set up over the heads of each participant to show their memos to each other. Through analysis from a comparison experiment, we discuss the effectiveness of the ME.

Keywords. Design collaboration; face-to-face meeting; room ware; co-occurrence networks analysis; and semi-public discussion media.

1. Introduction

Our research group has been developing a computerized environment for synchronous and asynchronous design collaborations (Matsumoto, 2006; Saji, 2006a; Yamaguchi, 1999; Yamashita, 2006). Also we have been researching the workplace for knowledge-based work, including meeting spaces (Saji, 2006b; Kim, 2008). This paper describes our current study in the development of a face-to-face design meeting environment that considers the integration of IT and architectural space.

In today's knowledge-based society, more and more creativity in the design activities is expected and the importance of design collaborations, which is one good way to create new values, is increasing.

Using a whiteboard and projector is a typical style of face-to-face meetings now. This equipment is exceedingly public media; however they are also valuable media for sharing information among group members. Meanwhile, memos, which many people take in their own way during meetings, are very private media. This is because such personal memos often include variety of ideas, awareness, understandings or points, that the authors think a personal memo has the potential to activate design discussions more and more. The point is that semi-public media is important but insufficient for face-to-face meetings, especially in the early design phase when we spread ideas.

In addition to our previous works (Yamaguchi, 1999; Yamashita, 2006), as influential past researches on this study, there is The Colab (Mark, 1987) which is one of the originators of room-ware, whiteboard based local/remote meeting room-ware (Rekimoto, 1998), and Roomware (Streitz, 2001) which is a total environment for collaboration.

2. Development of the Memo Externalizer

2.1 CONCEPTS OF THE SYSTEM

In this study we develop a new communication media named the "Memo Externalizer (ME)" which externalizes an individual's awareness and ideas in design meetings. The following are its three concepts:

- Expands the usual behaviours and gets assistance from computers without being aware of the man-machine interaction.
- Picks up on an individual's awareness and ideas which are buried.
- Supports the spread of ideas by being a "bridge" that connects member's personal ideas and the group's discussions.

This study focused on "personal memos" as something that can externalize awareness and ideas in meetings. Usually, a memo is an individual tool to record necessary information or to write down one's awareness. Each member has different points of focus, awareness, findings etc., and thus the contents of each member's memos are different from others.

The authors therefore propose a new system to support the picking up of information, which is buried between the shared information among the group and personal ideas.

2.2 OUTLINE OF THE ME ENVIRONMENT

The ME is a very simple system that use lightweight technologies. We have developed a system where a web-camera captures each individual's memo-taking and displays it on a screen, enabling the other members of the meeting to see the contents. The memos are shown on the monitors above each person's head. Simply put, this interface is exactly like the balloon of Manga. As shown in Figure 1,2, this environment consists of 5 components: 1) Web-camera; 2) Drawing board; 3) Monitor; 4) Host PC; -5) Interface program.

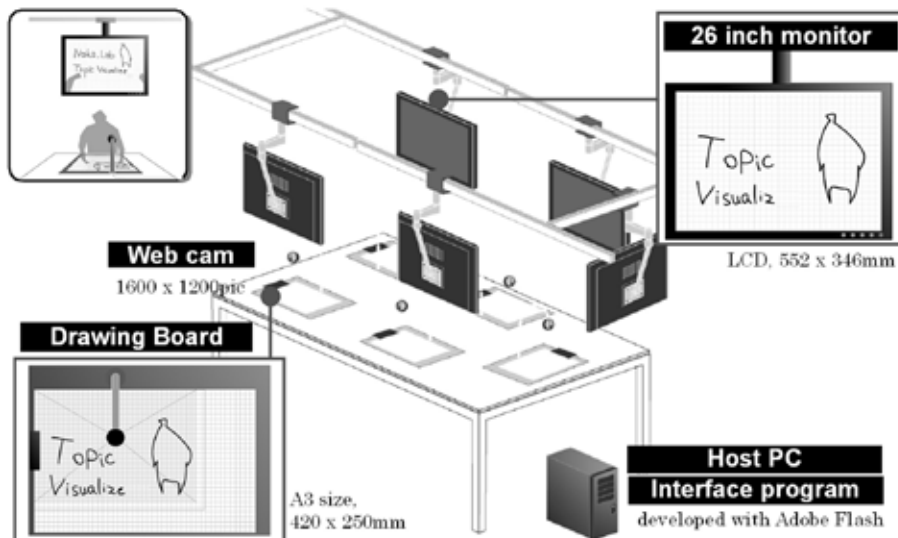


Figure 1. Composition of the ME



Figure 2. ME environment (left: Whole composition, right: drawing board and web camera)

The memo that is written on the drawing board is filmed by the web-camera, and then uploaded to the host PC as video data. The video is then shown on the monitor through the interface program. The web-camera is attached to the drawing board, so that the user can use it in a comfortable position. Also, from the requests received during our preliminary experiment, the authors left a little area for completely private memos in the corner of the drawing board.

In this environment, users just take a memo on the paper on the drawing board as usual without having to do anything special. The reason why a touch panel or a digital pen is not employed in this system is that the authors recognized the importance of unconscious support to usual behaviour through our preliminary experiment testing of digital writing devices. Also, we choose to film each person's desktop, so that they could also share hard-copy documents which they had brought in.

3. Outline of the evaluation experiment

In order to verify the effects, we carried out a comparison experiment between the ME environment and the normal environment (using whiteboard and paper). Each experiment lasted for 45 minutes. There were 20 participants (4 teams, 5 people each). Each meeting was given design assignments which we had made, based on past entrance exams of our school, in order to standardize the difficulty level of the assignments.

- **Assignment 1:** Ideas for a new table where many people can work joyfully
- **Assignment 2:** Ideas for new playground equipment in a kindergarten

In addition, in order to reduce differences in the meeting process among the different teams, we explained the rough schedule before starting the experiment. Furthermore, the orders of the given assignments and used environments were switched during the experiment, because we wanted to minimise the influence of the order of the environments (whether the ME is used first or last) on their assignment performances.



Figure 3. Two Environments of The Evaluation Experiment

4. Analysis of the evaluation results

From the above-mentioned experiment, we collected 1) Video records, 2) Recordings of speech, 3) Subjective evaluations (questionnaires and interviews), and 4) Images of the memos captured every 30 seconds.

4.1 FEATURE ANALYSIS OF THE MEMOS

In this analysis we categorized the participants' usages of the memos by the captured images of the memos every 30 seconds and the video records, and then studied their characteristics. For the categorization, we used “personal/group” axis and “keyword-type/sketch-type” axis, the former shows the target and the latter the content of the descriptions (Figure 4).

As a result, 37% of the memos were used for arranging the keywords of a discussion, 33% of the memos were used for personal sketches or diagrams, 20% were for personal keywords, and 10% for diagram to organize discussion. This result shows that the participants were actually using the ME to write down personal awareness as well as the shared information of the group.

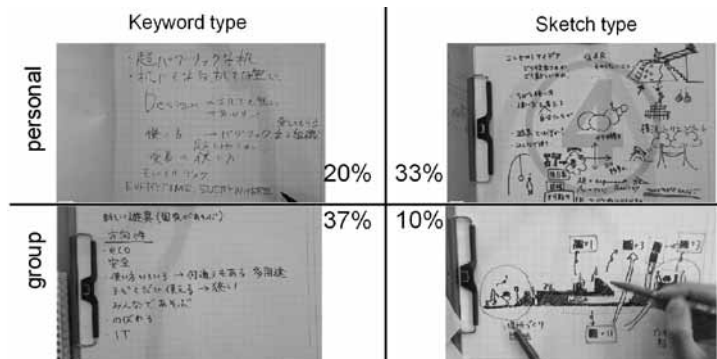


Figure 4. Four Types of Usages of the Memo

4.2 RESULTS OF THE QUESTIONNAIRE SURVEY

As shown in Figure 5, the results of the questionnaire (4 categories, 3 or 5 items each, with a scale from 1 to 7) show that the ME environment scored higher marks in most of the categories, such as communication, facilitation of discussion, and idea making, when compared to the normal environment. The ME environment had a particularly big effect on the items related to communication such as “Understanding others’ speech”.

Results that the ME environment had higher scores for “participating in the discussions” is also supported by the free comment “It enables us to com-

municate without speaking”. We can thus say that the ME was used as a media for participating in discussions via means other than speaking.

On the other hand, the normal environment scored higher marks in only two items, which were “Concentrating on the discussions” and “Sense of achievement”. As for the evaluation of the item “Concentrating on the discussion,” this can be explained by the high cognitive load on the participants in the ME, as some participants commented in the questionnaire “We were too focused on the memos”.

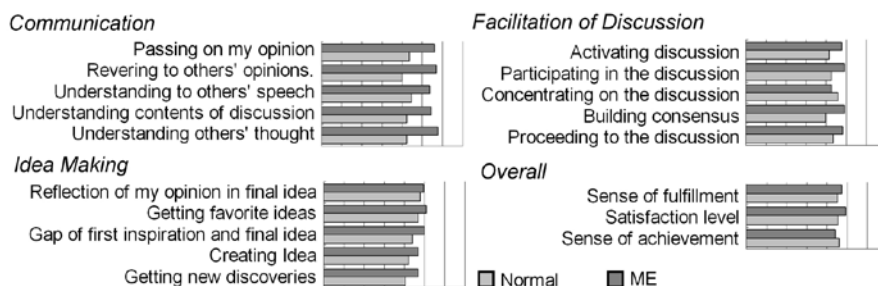


Figure 5. Result of the Questionnaire Survey

4.3 ANALYSIS OF SPEECH

Secondly, we analysed the effects of the ME environment by using the “speech sheet”. The speech sheet was made by transcribing the participants’ speech from the video record and IC recorder, without summarizing. In so doing, we added <speaker> <content of the speech> <silence> <accessing the memos>. Based on these five parameters, the authors analysed the following four points; from 4.3.1 to 4.3.4.

4.3.1 Amount of speech and Silence

The frequency of speech by the meeting members did not change, but the total number of letters (number of Japanese characters) in speech increased in the ME environment in three out of the four teams (Figure 6). A scene, which didn’t have any statements for longer than 5 seconds, was counted as “silence”, and we compared the number of seconds of the silences. The result was that 3 out of the 4 teams had less silence time in the ME environment (Figure 7). This is possibly because the ME externalized the discussion keywords, which improved the flow of the discussions. During the post-experiment interview, Team Y, the only team whose silence time increased, commented that they didn’t feel uncomfortable when they were silent, because they were communicating by the ME.

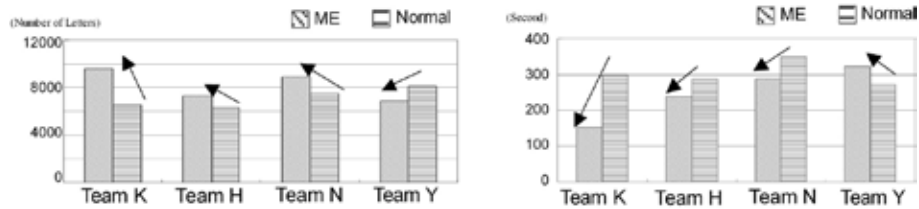


Figure 6. Total Number of Letters; Amount of Speech. Figure 7. Total Silence Time

4.3.2 Changes in the amount of speech

The graphs in Figure 8 show the change in the number of letters used in the speech of each team. All teams showed an increased number of letters in their speech at the initial stage of sharing the discussion targets. We can therefore say the ME is effective in invigorating discussions at the “kick-off”.

In addition, except for Team Y who had more frequent silence time, the rest of three teams had an increase in the number of letters in their speech in the ME environment. We speculate that this is because the referred keywords and materials in the discussions are externalized and are still available, which gives a positive influence on the invigoration of the discussions. On the other hand, none of the teams managed to finish the assignment within the time limit in the ME environment. This may have influenced the low scores for “achievement in the discussions” in the questionnaire survey.

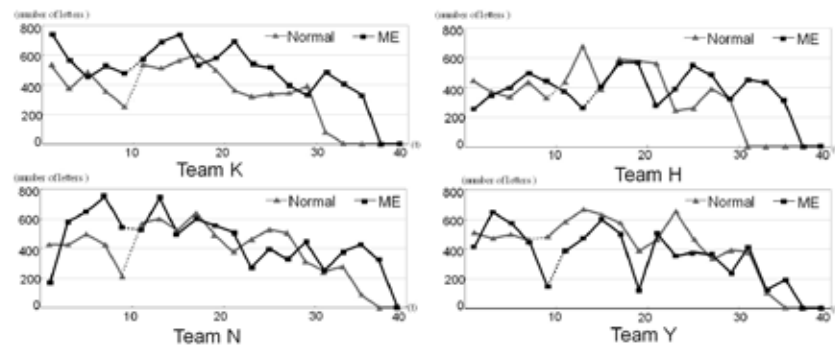


Figure 8. Change of the Number of Letters in the Speech

4.3.3 The number of citation speeches

By watching the video recording, we counted the number of “citation speeches” (the speeches which were made while the speaker was consulting written contents) that were based on the information externalized by the ME

or the whiteboard. As a result, the number of citation speeches of three out of the four teams increased (Figure 9).

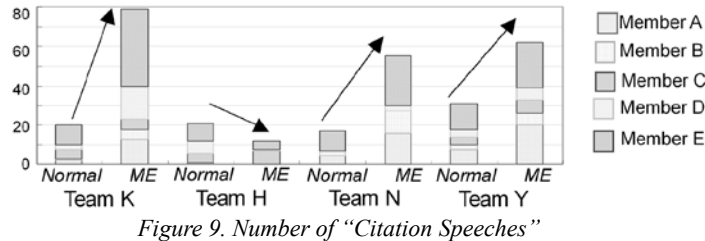


Figure 9. Number of "Citation Speeches"

4.3.4 Change in information access and the amount of the speech

Figure 10 is a graph which indicates the change in frequency of externalized information access*1 per unit time and also the amount of speech. This paper, incidentally, shows the graphs of only two teams who used both the ME and whiteboard in the experiment. We can see from the graph that-, while the ME is used throughout the time of meeting, the whiteboard is used only locally. This is because while the whiteboard is used as a media to write down the group's shared information, the ME serves as an intermediary media between the personal and the group media before shared information is created within the team.

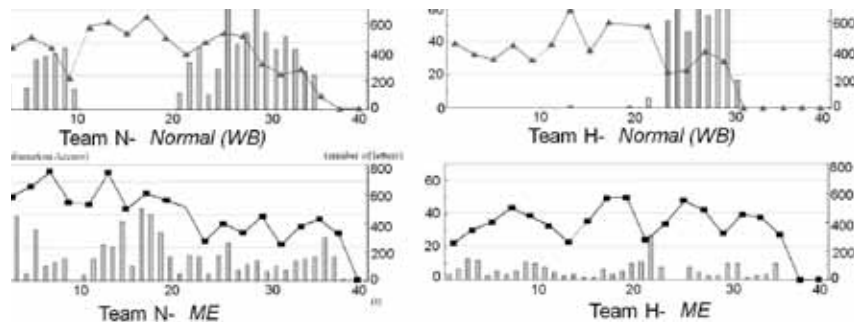


Figure 10. Change in Frequency of Information Access and Amount of the Speech

4.4 CO-OCCURRENCE NETWORKS ANALYSIS OF THE DISCUSSION

Finally, we made a co-occurrence network analysis of the conversations that took place, a kind of text-mining method, in order to compare the state of idea creation. Here we treat the co-occurrences in speech as connections within a discussion, and by visualizing them as networks, we can see the spread of

ideas in the shaping process of discussions.

Co-occurrence networks are a graph where words with similar appearance patterns, in other words, words with a high rate of co-occurrence, are connected by lines. In this study, we extracted nouns from the speech in each meeting, using a morphological analysis. Any the nouns which appeared more than five times were defined as keywords. When these keywords were used together within the same speech, we treated this as a co-occurrence, and we created a co-occurrence network graph (Figure 11). Using this graph, we examine how the ME changed the citation relations in the speech and how it changed the way ideas are spread.

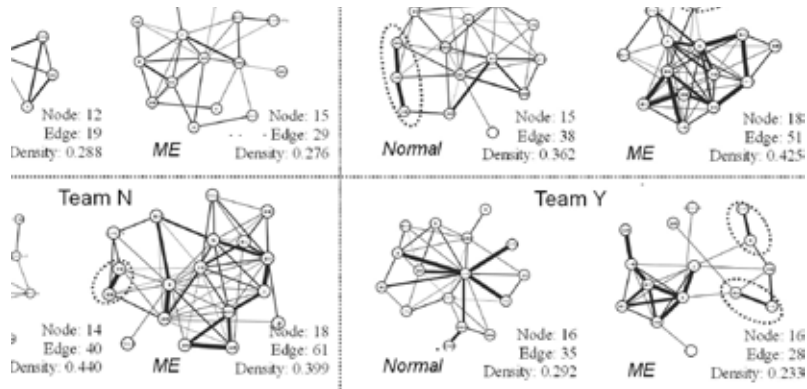


Figure 11. Co-occurrence Networks Graph

The nodes (nouns that appeared more than five times) and the edges (the co-occurrence relations) both mostly increase in the ME environment, and we can see that each connection between the keywords is stronger. Additionally, there is also an increase in the number of keywords which appear in association with other speech contents. This tells us that ideas can more easily be spread in the ME environment.

Regarding the co-occurrence relations as the connections between speeches, the increase in co-occurrence relations means discussions are now more easily connected. This suggests that the ME helps the process of shaping up the discussions.

Moreover, we can say that the weak-bonds which connect to the clusters of strong-bonds play a role in connecting ideas from different perspectives. That is to say, they bring new perspectives into the discussions and spread ideas. When we look at each network, though very subtle, we can see that in the ME environment there are more weak-bonds which have the “bridging function” to connect clusters of strong-bonds*2. This suggests that the information

externalized by the ME connects new opinions and ideas towards a certain direction, and spreads ideas in the discussions.

5. Conclusions

This paper proposes a new face-to-face design meeting environment; the Memo Externalizer. One of the biggest merits of this environment is that special construction work is not required and that it can be provided in any regular meeting room just by setting up monitors with poles or frames.

Results from the experiment illustrate its effectiveness and potential for facilitating meetings, activating discussions, and also spreading ideas. In conclusion, our trial in this study provides an example of the support environment for enhancing creativity of design collaborations in knowledge-based society; when very small ideas might come to have a big value.

Endnotes

1. "Access" here refers to an act where a participant of the experiment sees externalized information. The frequency of information access was counted by watching the video record (clearly looked at a monitor or WB).
2. We have used the Jaccard coefficient for the measurement of the co-occurrence, and we defined the bond as strong when the Jaccard coefficient is 0.1 or greater.

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THE ROLE OF COLLECTIVE INTELLIGENCE IN DESIGN

A protocol study of online design communication

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Abstract. Web-enabled collective intelligence in design invites anyone to contribute to a design process through crowd-sourcing. We use a protocol analysis method to analyse the forum data on a collective intelligence web site, studying communication among individuals who are motivated to participate in the design process. A protocol analysis allows us to compare collective intelligence in design to similar studies of individual and team design. Our analysis shows that a design process that includes collective intelligence shares processes of ideation and evaluation with individual and team design, and also includes a significant amount of social networking. Including collective intelligence in design can extend the typical design team to include potential users and amateur perspectives that direct the design to be more sensitive to users' needs and social issues, and can serve a marketing purpose.

Keywords. Collective intelligence; design process; protocol analysis; design communication

1. Introduction

As knowledge workers become geographically dispersed, and increasingly contribute to projects outside their regular employment in what Jeff Howe describes as their 'spare cycles', a growing need for networked communication tools that support distributed, informal collaboration has become apparent.

Some online communities, such as *Quirky.com*, *MyooCreate.com*, *99Designs.com* and *OpeningDesign.com*, that recognise the value in attracting

diversity of opinion and supporting various levels of volunteer involvement, have emerged in the design domain. *Quirky* is a platform for collaborative product development, where the community works together with a dedicated in-house design team to bring products from idea to market. *Myoo* (me + you) *Create* provides a platform for designing solutions for environmental and social issues. *99Designs* (along with many other graphic design sites such as *TopCoder Studio* and *DesignCrowd*), crowd-source logos, websites and other marketing needs - and show that a company can receive a massive pool of unique conceptual designs by leveraging the diversity of the crowd through competition. *OpeningDesign* is a recently launched platform for architecture and urban planning, involving various stakeholders of a project and providing a space for opinion polls and crowd-sourcing jobs.

These platforms rely on community participation, both amateur and professional, and their websites support public discussion at multiple levels of involvement. They attract a range of inputs, from the casual observer who might be motivated to comment once or twice, to the active contributor who closely tracks progress and responds often and with minimal delay. While we don't always see the full spectrum, we are seeing different levels of engagement as described in the Reader-to-Leader framework for technology-mediated social participation (Preece and Schneiderman, 2009).

2. Studying design by protocol analysis

Protocol studies of designers provide an analysis of the design thinking process. The 1996 Delft workshop on Analysing Design Activity (Cross *et. al*) provided recorded data of both individual and co-present synchronous team design activity. The many papers that resulted from the workshop compared and contrasted these two ways of designing using different coding schemes to highlight different design models and processes. Since design communication can now be computer-mediated, protocol analyses have been applied to team communication via computer interfaces (see for example, Gabriel and Maher, 2000). Now that the social web has become mainstream and design platforms are supporting crowd-sourcing and the many incarnations of collective intelligence, we can apply protocol analysis to design communication in collective intelligence approaches to designing.

Studying collective intelligence in design is a progression in design research where a key communication variable has been changed: from team co-present synchronous communication, to distributed team computer-supported-synchronous communication, to collective computer-supported-asynchronous communication. This leap to collective intelligence or crowd-sourcing supports design communication through asynchronous discussions

and scales up design participation through an open invitation to the world. In this paper we begin to examine the role crowd-sourcing plays in design by analysing asynchronous design communication from the Quirky web site.

3. A study of design communication

Our study of collective intelligence varies from traditional protocol analysis in design research in employing an ethnographic method of enquiry, using case studies rather than controlled experiments. The data was collected from the discussion forums associated with publicly available design projects on the Quirky web site. There are two main approaches to analysing designing: (i) process oriented analysis, which examines problem-solving actions and design strategies; and (ii) content-oriented analysis, which focuses on “what designers look for, see, do, and possibly think” (Dorst and Dijkhuis, 1995). Our study combines the two by first coding according to design process and then coding the content within each process.

3.1 QUIRKY.COM OVERVIEW

Quirky was selected for analysis as it is a commercially successful example of an open community used in design practice and a readily available representative of a class of systems for collective design.

The Quirky website gathers new product ideas from individuals and presents them to the crowd, effectively an ideas popularity contest. Each week, the new product idea with the most votes is selected for development. The crowd is sourced from people who choose to participate and make contributions, and these volunteers are involved in the design process at key stages, such as during ideation and evaluation. The overall design process and major design decisions are managed by a dedicated in-house design team. This dualistic model relies on both a design crowd and a design team, and uses communication tools and platforms to bring out the strengths of each in order to quickly bring products to market in a profitable way.

Design development time is typically very fast. For example, the Switch Modular Pocket Knife was developed in about a month, with four days spent on industrial design, four days on a second iteration of industrial design, one day on product naming, four days on coming up with a tagline and three days on logo design.

Design activity by the crowd is both textual and visual (images and video). Design communication between the crowd and the team is web-based, with forum pages dedicated to each aspect of product development. Design activity by the team takes place offline, with the outcomes of each stage in product

development made available online to the crowd.

3.2 SOURCING AND SEGMENTING THE DATASET

Design communication data was obtained from three different product design public forums on Quirky.com: a waffle maker, a switchblade, and an iPad cover. These three projects were selected for analysis from the range of completed designs available online. The forum data for each project comprise a continuous stream of chronologically ordered text. Segmentation occurred at three levels: the speaker level, the sentence structure level, and the code level. At the first level, the data was segmented whenever a new person added a comment. At the second level, each person's comments were segmented at sentence breaks. At the third level a sentence was segmented so that each segment could be assigned only one code. The number of segments for each design case is: waffle maker: 265 segments, switchblade: 426 segments, and iPad cover: 88 segments.

3.3 CODING SCHEME

We started with the design communication coding scheme for analysing team design communication about design ideas in Gabriel and Maher (2000): Introduction, Acceptance, Rejection, Clarification, Confirmation, Development, Repetition, Referencing, Revisiting, and Evaluation. A pilot study applying these codes to our data set revealed that these ten codes, being developed for coherent design team communication, were not all appropriate for design crowd communication. For example, Revisiting assumes that the members of the team are all present and are recalling a previous part of the discussion. In a design crowd all individuals are not present at the same time and revisiting an idea does not have the same meaning. We clustered these ten codes into three groups: Ideation, Evaluation, and Referencing as a way of comparing our results to the Gabriel and Maher results, and to provide meaningful codes for design crowd communication.

When we coded the dataset to this higher-level of classification we added two codes: Qualification and Social communication. Qualification is applied to segments that establish the credibility of the individual's contribution, such as describing the history of their use of the product undergoing development. Social communication is applied to segments that have commentary of a general, social nature, such as emoticons, funny asides, or words of encouragement.

To understand the aspect of the design product being discussed in ideation, evaluation and referencing, we applied Gero's FBS ontology (Gero

and Kannegiesser 2007). For example, Ideation – function is assigned to a statement that is about a design idea related to the function of the design, that is, its purpose; Ideation – behaviour is a statement about a design idea related to the behaviour of the design, that is, its performance or other feature derived from the structure of the design. Similarly, Ideation – structure is about a geometric or material property of the design. Our final coding scheme is shown in Table 1.

Table 1. Final protocol classifications

Term (abbreviation)	Description
Ideation – function (IF)	A concept dealing with the product's purpose or user needs
Ideation – behaviour (IB)	A concept for how the product, or a feature of the product should perform: what it does
Ideation – structure (IS)	A concept related to the product's physical properties: how it should look or how it is composed
Evaluation – function (EF)	An appraisal of the product or concept's purpose
Evaluation – behaviour (EB)	An appraisal of the product or concept's ability to perform or do something
Evaluation – structure (ES)	An appraisal of the product or concept's physical properties: how it could look or how it might be composed
Referencing - function (RF)	Referring to an existing product's function.
Referencing – behaviour (RB)	Referring to an existing product's behaviour.
Referencing – structure (RS)	Referring to an existing product's structure.
Social Communication (SC)	Commentary of a social nature.
Qualifications (Q)	Establishing an individual's background to support opinion
Uncoded (U)	Unclassified segment

3.4 PROTOCOL CODING PROCESS

We first coded segments into Ideation, Evaluation, Referencing, Qualifications and Social communication. For Ideation, Evaluation, and Referencing segments, we further coded them as F, B, or S. This further coding required more deliberation to disambiguate F, B, and S. An example of this is the design discussion of the waffle maker, where one person commented: “With all this talk of non-stick, I believe silicone molds [sic] and/or surfaces would be the solution.” In this example, ‘non-stick’ is the context in which silicone moulds were proposed. Although non-stick-ability in this context is behaviour of the product, the proposed idea related to the product's physical properties and therefore the segment was coded as ideation-structure. Ideation-function was determined by user needs, as in the example: “It would also be nice to offer a solar powered option for the 2 or 3 seasons when most people are camping”. The segment immediately proceeding: This flexibility would really help it to reach a broader market”, (also by the same person) was coded as ideation-behaviour, as the marketability of a product is a behaviour of the product.

Evaluation ranged from mentioning the pros and cons of the various ideas to commentary of a more general nature aimed at verbalising support (i.e. “Love this idea!”). If the person described what it was about the product they loved, it was classified accordingly. For example in the Switch pocket knife dataset the segment: “I love the idea of being able to pick what is included” was coded as evaluation-function, as the ability to select components is a user need. An example of evaluation-behaviour was the segment: “For any sustainability this would have to be a high quality unit, if you cut corners you would never get the cult following necessary for this to travel word of mouth”. Sustainability and cult-following are behaviours of the product. If an evaluation segment alluded to the structure of the product, it was classed as evaluation-structure, such as: “Unfortunately, I think you might have to jettison the idea of modularity!”

It was more difficult to classify Referencing into FBS as often the required information was not provided. Referencing often took the form of links to external webpages. In a large number of cases, the link was provided without any accompanying text, or the accompanying text was classified as general discussion such as, simply: “inspiration”.

3.5 RESULTS

Table 2 shows the percentage of segments in each of the top level codes.

Table 2. Quirky Data Top-Level Results

	Waffler %	Switch %	Cloak %	mean %
I	27	33	44	34.67
E	24	22	31	25.67
R	12	8	8	9.33
S	34	36	17	29.00
Q	1	1	0	0.67
U	2	0	0	0.67

The majority of segments were within three areas: Ideation (34.67%); Social communication (29%); and Evaluation (25.67%). Referencing was 9.33%; and Qualifications and Uncoded segments were both 0.67%.

Table 3 shows the percentages of segments in the content areas of Function (F) Behaviour (B) and Structure (S) within each of the top level design process codes. U indicates that the segment did not correspond to F B or S, that is, Uncoded. Within Ideation, all segments were related to F, B, or S, and the greatest focus by far was on Structure (IS=58.3%) followed by Behaviour

(IB=23.33%) and Function (IF=23.33%). Evaluation showed a similar breakdown with 47.33% dedicated to appraising Structure (ES), 29.33% for Behaviour (EB) and 22.67 for Function (EF).

Table 3. Quirky results breakdown

	Waffler %	Switch %	Cloak %	mean %
IF	28	15	13	18.67
IB	19	25	26	23.33
IS	53	60	62	58.33
IU	0	0	0	0.00
EF	11	24	33	22.67
EB	34	35	19	29.33
ES	53	41	48	47.33
EU	1.6	0	0	0.53
RF	9.7	11	14	11.57
RB	29	24	0	17.67
RS	13	43	86	47.33
RU	48	22	0	23.33

The largest number of uncoded segments occurred in Referencing (RU) with 23% as opposed to 0.53% for Evaluation and 0% for Ideation.

4. Observations and analysis of results

Protocol analysis proved to be a useful method for gaining insight into the role of collective intelligence in design. The development and modification of the coding scheme provides some insight into the nature of communication in design crowds. We observed that individuals were not interacting synchronously or continuously, but engaging on the forum at various times over an extended period. Not all individuals were keeping track of the history of design communication, which resulted in recently added design commentary often being very similar to those previously stated - not a simple case of revisiting or repetition, but of two independent, but essentially identical contributions.

We also observed that participants were augmenting their design contributions with social discourse not directly related to the design, but instrumental in persuading individuals of their view or for establishing credibility and rapport. Two additional communication codes were added to describe this dataset: 'social communication which consisted of emoticons, jokes, and comments such as "so...hmmmm"'; and 'qualifications', which occurred when users voluntarily stated their past experience or credentials in

order to convince the community that their contributions had value.

Qualifications segments did not occur in as large a proportion as we had anticipated. Other collective intelligence in design sites, such as TopCoder, incorporate complex qualification measures into their user profiles, so having such a low rate in this dataset may be a reflection of Quirky's system structure, where domain expertise lies mostly with their dedicated in-house design team. This low score for qualifications is similar to the low mentions of qualifications among team designers, but for a different reason: members of design teams have existing, established and recognised credentials and don't need to remind each other of their backgrounds. In many cases in team design, individuals had been selected specifically for what each member can bring to the design process. In the examples of crowd-sourcing studied here, members know each other only by their screen name. As the same core group of members work on multiple projects together, they may build up a rapport and shared history, but if establishing qualifications was so important, they would still need to convince new members of their qualifications with each post, as they cannot rely on them to have canvassed and remembered comments from the past or from other forums. From this, we can assume that establishing qualifications do not hold a great deal of importance, and that members behave in an egalitarian manner.

Social communication was a relatively large percentage of the communication content. Being part of the community may be strong motivation for people to contribute to these sites (see Maher et al 2010). Socialising is a natural human behaviour to help create and reinforce bonds. Since the text-based forums strip individuals of body language and tone, they find other ways of establishing rapport. Emoticons and general social comments fill that need. Since they have no regular meeting space outside of the forum, these behaviours occur within the design forums.

The vast majority of the crowd's contributions, both in ideation and evaluation, lie in the area of product structure. The psychological response to product form is perhaps one of the most fundamental components of a purchasing decision (Bloch 1995), and the design crowd is largely composed of end-users (more so than the design team). Although end-users have a vested interest in ensuring the product suits their needs (function), these needs are often not as highly articulated as opinions on aesthetics and composition; attributes which arise directly from those needs.

5. Conclusions

The Quirky approach to design provides a successful template for incorporating an open, diverse crowd into the design process. It recognises the strengths of

the crowd and the design team, and organises them in such a way as to bring the most out of the interaction. By recognising the crowd as a potential future market and understanding the benefits of placing end-users within the design process, Quirky leverages the crowd's diversity of opinion at the key stages of ideation and evaluation to broaden the solution space and ensure the product design evolves in the direction of popular appeal.

In the following paragraphs, we comment on key aspects of the nature and role of the crowd in current collective intelligence in design communities.

Managed vs. Self-organised: The crowd is an amorphous entity, with individuals partaking in varying degrees. Although each individual is motivated to participate, the crowd lacks organisational structure. In some cases a crowd can be efficient at self-organising and achieving a great many things within imposed time constraints, such as the I Love Bees game (McGonigal 2008), which reached the objectives of the game's designers with no externally imposed organisation or rules. With I Love Bees, the crowd was of an extremely large size (over 600,000 participants), most of who were devoted fans of the existing Halo computer game. In contrast, Quirky's crowd is small in number, with usually only a dozen regular volunteers on any given project. Added to this is the pressure of bringing a product to market in a timely fashion, and to have a mechanism for decision making. Quirky have addressed this by hiring a dedicated, experienced, in-house design team to take responsibility for the product's progress.

Users as designers: Advertisers run focus groups to gauge how best to present a product according to the user's needs. Producers screen films to preview audiences to assess their reaction and make editorial changes to the material in accordance with their findings. It is also beneficial to include end users in product design. Enduring involvement with a product gives individuals a greater sense of emotional connection with the product; a higher likelihood of purchasing the item and higher rates of reported satisfaction with the product after purchase (Sharon et al 1988). No involvement is more enduring than following a product from idea to market. This seems to be supported by the success of Threadless.com for crowd-sourced t-shirt design; RYZ.com for sneaker design and Quirky.com for product design. Since the members of a crowd are already significantly invested in the product in terms of an emotional connection over time, but can also be financially vested (top influencers at Quirky get a cut of the profit), they are more likely to purchase the product and tell people about it.

Our conclusions are based on an analysis of data from three projects on Quirky and our observation of other web sites that crowd-source design activity. Although generalised statements about collective design cannot be

made with a sample of this scope, the observations and experiences outlined here identify key patterns that will benefit from further investigation. An additional contribution of this study is a methodology for analysing collective design, which is useful in an area of research that is still forming.

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MOTIVATION, CYBERWORLDS AND COLLECTIVE DESIGN

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Abstract. Collaborative design is characterised by small-scale, carefully structured, professional design teams. The increasing popularity of social computing and mass communication supported by cyberworlds suggests there is now also a strong possibility of design through mass participation, beyond small-scale, collaborative design scenarios. However to achieve collective intelligence in design, there is a need to motivate large groups of users to contribute constructively to design tasks. This paper studies different types of cyberworlds to classify the motivation profiles of their user bases. We compare these motivation profiles to those required for the emergence of collective intelligence and develop a list of technological requirements for cyberworlds to support collective intelligence and design.

Keywords. Collective intelligence; design; motivation; cyberworlds.

1. Introduction

Collaborative design is relatively well understood in the literature, and is characterised by small-scale, carefully structured, professional design teams. The increasing popularity of cyberworlds – including social networking sites (SNSs) and virtual worlds (VWs) – suggests there is now also a strong possibility of design through mass participation, beyond current small-scale, collaborative design scenarios. Cyberworlds are already a recognised platform for collective intelligence (CI) (Levy, 1997), a form of group intelligence that emerges from collaboration and competition among large numbers of individuals. CI games such as *I Love Bees* (McGonigal, 2008), and applications

such as NASA's *Clickworkers* (Romero, 2009), have demonstrated the capacity of CI to solve complex problems. Directing CI for design purposes creates the concept of 'collective design'. Collective design is defined as large-scale participation from both professional and non-professional designers in increasingly complex and challenging design tasks, beyond small-scale collaborative design scenarios (Maher et al, 2010). To achieve this, however, an understanding is required first of what motivates individuals to contribute constructively to CI applications, and secondly which components of existing cyberworld technologies are necessary both to foster CI and to support design.

Section 2 of this paper reviews four human motivations relevant to CI and design: activation, achievement, affiliation, and power. These motivations are closely related to the explorer, achiever, socialiser and killer user types proposed by Bartle (2003) for VWs, but extend to cyberworld users in general. Section 3 studies a number of different types of cyberworlds, including VWs, SNSs and CI applications to classify the user types they support and identify the technical components that support these users. Section 4 summarises cyberworld technologies and their capacity to support a combination of CI and design, based on their capacity to support and encourage achievement-motivated behaviour. A list of technological requirements (and non-requirements) is proposed for cyberworlds to support CI and design. In particular, we emphasise the need for such applications to attract achievers and explorers, while either minimising socialisers and controllers, or redirecting these roles for a more positive impact on collective design.

2. Motivational psychology and cyberworld user types

Bartle (2003) identified four types of VW users: explorers, achievers, socialisers and killers. With the emergence of new cyberworld phenomena such as SNSs, these user types maintain some relevance as categories for types of behaviour that may be exhibited by users. This section reviews the motivational psychology that distinguishes each category, and considers which types of behaviour need to be harnessed for CI to emerge.

2.1. THE PSYCHOLOGY OF ACTIVATION

Activation is associated with electrical activity in the brain (Moruzzi and Magoun, 1949). Conditions of activation range from sleep and sleepiness to high levels of excitation. These conditions have been found to accompany changes in performance proficiency on a variety of tasks, with intermediate levels of activation most conducive to performance (Heckhausen and Heckhausen, 2008).

Activation psychology is relevant to our study of cyberworlds and design because it is closely associated with curiosity, creativity, exploration and aesthetic appreciation. Berlyne developed the most extensive theory of motivation based on the principals of activation and arousal (Berlyne, 1960). Berlyne distinguished between states of high and low arousal, suggesting that high arousal results in focused (specific) exploratory behaviour while low arousal leads to diverse exploration or curiosity. He used his findings to develop a psychology of aesthetics that describes how observers can be pleasantly stimulated by artworks or designs because they can bring their activation to an optimal level. A work of art or a design can also be experienced as unattractive or repellent if the observer finds it too novel or complex. Berlyne also distinguished between arousal levels and positive or negative hedonic (pleasure) values resulting in approach or avoidance tendencies to arousal. Once a certain threshold has been crossed, positive hedonic values builds to a peak as arousal potential increases. Any subsequent increase in arousal potential leads to a decline in hedonic value and eventually to increasing negative values.

The psychology of activation is thus closely associated with design, exploration, creativity, novelty, and pleasure (the ‘fun-factor’). Exploratory behaviour is relevant in new cyberworld types such as SNSs that permit individuals to explore other people’s pages, create their own pages and gain pleasure from these experiences. Furthermore, exploratory behaviour is likely to be important to harnessing CI in design as exploratory activities can gather information on how the cyberworld works and how various design tasks can be completed and can identify unexpected features or ‘bugs’ in applications (Bartle, 2003).

2.2. ACHIEVEMENT MOTIVATION

Achievement motivation drives humans to strive for excellence by improving on personal and societal standards of excellence (Heckhausen and Heckhausen, 2008). Achievement motivation determines how individuals evaluate the tasks set before them and how they select which tasks they will work on. Atkinson (1957) defined achievement motivation in terms of conflicting desires to approach success (success-motivation) or avoid failure (failure-motivation). Success-motivated individuals will choose tasks of moderate-to-high difficulty to challenge themselves and progressively increase their skill-sets.

Achievement motivation is relevant to CI in a number of ways. First, the opportunity to self-select and work on tasks independently has a positive effect on task motivation. This is important because CI relies on voluntary participation. Secondly, a majority of motivators of CI participants are

achievement related. These include participation to contribute to a wider cause, for the challenge, for career advancement, for reward, or out of a sense of duty (Maher et al, 2010; Malone et al, 2009). Supporting achievement-oriented behaviour is likely to be a critical to harness CI and design because they are the behaviours that will meet the design goals of the CI application.

2.3. AFFILIATION MOTIVATION

Affiliation refers to a class of fundamental social interactions that seek contact with formerly unknown or little known individuals and maintain contact with those individuals in a manner that both parties experience as satisfying, stimulating and enriching (Heckhausen and Heckhausen, 2008). Individuals high in affiliation motivation tend to initiate fewer acts that might spark conflict. This has the adverse effect of meaning that they also initiate less cooperative acts. Specific affiliation related goals include: being in the company of others; cooperating; exchanging information; and being friends. Affiliation motivation is relevant to almost all cyberworlds including VWs, SNSs and CI applications. Almost every type of cyberworld permits some form of communication, whether synchronous or asynchronous, and supports the formation of relationships and friendships.

Socialising behaviour maintains its relevance in recent cyberworld settings, but there is an important caveat with respect to CI applications. Individuals high in affiliation motivation without correspondingly high achievement motivation may not be interested in the achievement-related tasks that are the aim of the CI application. Rather they may make use of any available communication tools for unrelated social interaction. This can be to the detriment of the community's work focus.

2.4. POWER MOTIVATION

Power can be described as a domain-specific relationship between two individuals, characterised by the asymmetric distribution of social competence, access to resources or social status (Heckhausen and Heckhausen, 2008). Power is manifested by unilateral behavioural control and can occur in a number of different ways. Legitimate power, for example, is derived from norms internalised by one individual telling them that another individual is authorised to regulate their behaviour. Effective use of legitimate power assists the organisation of communities and allocation of work tasks. In contrast, coercive power is exerted if one person is in a position to withdraw the opportunities of another to satisfy their motives. Bartle's 'killer' user type

describes this latter type of power. Killers in his system use the tools provide by the game to impose on others, literally by killing their avatar or otherwise hindering their freedom of action.

In this paper we replace the killer user type with 'controlling' behaviour. Controlling behaviour comes in two types: 'leadership' which constructively organises action in the cyber-society and the 'killer' which prevent those actions from going ahead. For CI applications it is desirable to minimise the latter, while still encouraging the former.

3. Cyberworlds that support mass participation in design

Now that we have an understanding of the different behaviour types of cyberworld users, this section discusses three categories of cyberworld with respect to the behaviour types they support. Note that individual users may exhibit, or be encouraged to exhibit, more than one behaviour type. The categories of cyberworld discussed in this section are VWs, SNSs and specific CI applications. A number of examples of each are discussed, with particular reference to three examples that incorporate design tasks: *LEGO Universe*, *myLEGO Network* and *LEGO Factory*.

3.1. VIRTUAL WORLDS

VWs are related to architecture and design because they are characterised by the use of the place metaphor. Recent studies (Merrick et al, 2011) and applications (Rosenman et al, 2006) have shown that the combination of design and modelling tools, communication tools, and artificial intelligence in VWs makes them suitable platforms for supporting collaborative design, including human-human collaboration and human-computer co-creativity. Open-ended VWs in which participants can create new buildings or artefacts are particularly relevant to design. A number of these exist at present, including *Second Life*, *There*, *Kaneva* and *Moove Online*. However, these worlds do not have specific design-related goals. As such they tend to provide more support for socialisers, explorers and controllers than achievers. While this does not necessarily preclude the emergence of CI, this section focuses instead on a forthcoming VW called *Lego Universe* that takes a different approach.

Lego Universe is a new massively multiplayer online role-playing game with a unique combination of open-ended content creation and game-play. Users interact with the game using their own LEGO figure avatar. The game combines design/building, play and connection with friends in a 3DVW platform. Design/building is both a means of completing challenges and a reward for completing challenges. For example, a player might build a rocket

ship to use in a battle. If the player wins the battle they will be rewarded with LEGO bricks that they can use to create their own home, pets or other objects on their own virtual land. These creations can be brought to life using the LEGO visual programming language to implement behaviours.

The unique combination of challenges and design in a multiuser world means that *Lego Universe* requires achievement-oriented behaviour, socialising, exploration and leadership behaviours of its players.

3.2. SOCIAL NETWORKING SITES

A social network (Freeman, 2006) is a social structure made up of individuals (or organisations) called nodes. Nodes are connected by links such as friendship, kinship, common interest, financial exchange or beliefs. Originally, social networking referred to people in real life interacting with others. More recently, websites are being used for social networking as well. SNSs are web-based services that allow individuals to construct a public or semi-public profile within a bounded system, articulate a list of other users with whom they share a connection, and view and traverse their list of connections and those made by others within the system. These sites provide a platform for people and organisations interested in a common subject to connect and interact with each other. People can share pictures, videos, comments and web-links, among other items.

The *MySpace 08* report lists six types of SNS users (MySpace, 2008):

- *Essentialists*: use SNSs to connect with friends and family (38%).
- *Transumers*: join groups connected to their hobbies (28%).
- *Connectors*: pass on information and links whenever they come across something they find interesting (10%).
- *Scene Breakers*: find new bands and talents online and share them through the site (5%).
- *Collaborators*: use SNSs to create social events (5%).
- *Netrepreneurs*: use the SNSs for making money (4%).

If we re-evaluate these categories in terms of the four motivation types discussed in Section 2 then we can see that essentialists, transumers, connectors and scene breakers can be classified in the activation and affiliation categories. Only collaborators and netrepreneurs (<10% of users) can be classified in the achievement-motivated category. This suggests that SNSs such as *mySpace* and *FaceBook* in their current forms may not be suitable for supporting CI unless they can be adapted to better harness achievement-motivated individuals. One example of a SNS that seeks to do this is *MyLEGO Network*.

MyLEGO Network is a social networking game for children. When users

sign up, they create their own LEGO figure avatar. They can then create and personalise their own page with stickers and music. For safety purposes, because the site is for children, users can only communicate with each other via pre-written text so messages are limited to in-game content. Users may choose to participate in the game aspects of the network. In addition to humans, the *MyLEGO network* is populated with non-player characters. These characters trade LEGO blueprints in return for LEGO bricks that users can ‘grow’ on their home page. Once a blueprint is purchased, the model it describes can be built by locating and trading for its components. Players who create a variety of different models are rewarded with ranks. This draws on their achievement motivation to design/build. There are also different types of badges available for players who have completed certain specialist challenges. This supports both achievement and exploration-oriented behaviour.

3.3. COLLECTIVE INTELLIGENCE APPLICATIONS

CI applications may be VWs or SNSs, or may be in other forms. One example a CI application that doesn’t fall in the previous categories is *LEGO Factory*. Using *LEGO Factory*, people can design their own original custom *LEGO* model using the *LEGO Digital Designer* software. They then upload the model to www.legofactory.com from where they or others can purchase all the physical bricks and elements required to build the model in real life. The *LEGO Digital Designer* software automatically generates instructions for the new model. In this way, LEGO draws on the collective design abilities of a much wider community than their own paid designers to generate new LEGO products. To draw on the achievement-related motivation in their community of designers LEGO holds competitions such as the *Design byME Contest*. *LEGO Factory* does not include built-in communication tools, but communication between designers is supported by the Design byME forum. The separation between the communication and design tools means that there is also separation between the achievement and affiliation related tasks. This permits achievers to focus on design tasks without interruption, but to communicate with others when required.

Lego Factory is unique as a CI application because it supports and motivates a collective of novice designers to undertake the creative tasks of building design. This is quite different to CI applications such as *Google Cities in 3D* and *Google Building Maker* where the design tasks are often constrained to simulating existing physical buildings, or computer game modding which requires a certain level of expertise by participants.

4. From mass participation to collective intelligence in design

Section 2 identified achievement-oriented behaviour as most critical for CI to emerge in cyberworlds, followed by exploration to a lesser extent. Socialising and controlling behaviours may be useful, but are less critical. This section discusses how different technological components of cyberworlds can encourage or discourage each type of behaviour.

4.1. TECHNOLOGIES FOR EXPLORATION

Explorative behaviour is supported by cyberworlds that focus on world-oriented technological components that add depth, volume and complexity to a world (Bartle, 2003) rather than user-oriented components. Specific components that can encourage curiosity and exploration thus include:

- Large/complex worlds that require extensive exploration;
- Allowing anyone to design and extend the world. This means new content is constantly being added to explore;
- Many small tasks that can be solved easily;
- Commands that produce complex or entertaining outcomes.

4.2. TECHNOLOGIES FOR ACHIEVEMENT-ORIENTED BEHAVIOUR

World-oriented technological components also support achievement-oriented behaviour. Technologies for promoting achievement motivation include:

- Large/complex worlds with many challenges to achieve;
- Limited navigation options. This forces users to focus on tasks in their immediate area.
- Adequate navigation and user help tools such as detailed manuals and world maps. This permits users to focus on tasks without struggling with their orientation in the world;
- A straightforward, easy to understand interface;
- An extensive level or class system with rewards for achievement;
- Large and complex tasks that take longer time to complete.

4.3. TECHNOLOGIES SUPPORTING SOCIALISING BEHAVIOUR

Socialising behaviour is supported by communication technologies. The technological components suggested in this section should thus be included cautiously in a CI application to avoid encouraging too much socialising behaviour. Communication technologies are useful in CI applications, but it should be directed specifically for desired tasks, limiting their uses for pure social purposes. In addition, achievers often find a way to communicate if

required, even if they are not specifically supported by the CI application.

Technological components for supporting socialisers include:

- Communication facilities, including text, voice and other multimedia data, as well as emotes;
- World designed with effective chance encounter so that people are more likely to encounter each other;
- Increased methods of navigating between different world locations;
- Maximising the number of simultaneous players per server.

4.4. TECHNOLOGIES FOR LEADERS

As with socialising behaviour, the leadership sub-type of controlling behaviour is required in a limited way to provide organisation, direction and leadership in CI. The killer sub-type is generally undesirable. Many different types of 'killers' exist and there is a large body of computer security literature concerned with reducing the impact of this user type (Kabiri and Ghorbani, 2005). This section focuses instead on technological components associated with the leader sub-type. These include:

- Communication and coordination facilities;
- Group formation and management tools;
- Task planning, allocation and management tools.

5. Conclusion and future

This paper has reviewed four human motivations relevant to CI and design: activation, achievement, affiliation, and power. We argue that for CI to emerge, cyberworlds need to support achievement-oriented behaviour and exploration to the greatest extent, and support a limited amount of leadership and socialising behaviours to diversify the collective.

Based on the current study, our research will further the investigation of cyberworlds for collective design to specifically focus on the support of CI in design activities and for design purposes, in two main directions:

- (1) Further understand the potential of these four user types for collective design, in relation to different process models of designing; and explore more complex design scenarios where participants take on roles across different user types.
- (2) Develop technology spaces for the facets of cyberworlds that contribute to the support of collective design, including design and modelling tools, communication tools, artificial intelligence, level system, motivation, governance and other related facets; and understand how these facets

support the design, communication, motivational and educational requirements of collective intelligence applications.

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COLOUR-CODE MODELS: THE CONCEPT OF SPATIAL NETWORK

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Abstract. The main goal for the architects or planners is to understand a perspective of the user. The foundation of the design process is to create buildings and environments, which will be both innovative and functional for all types of users, including adults and children. While planning the environments for children the particular aspects should be considered. The important questions are: What kind of contact does child have with the city, urban places and buildings? How does the child construct the picture of the city? What kind of urban or architectural spaces contributes to the relation that a child has with the environment? Most of the previous studies concentrating on creation of spaces for children have focused on the perspectives that have adults. According to CAADRIA 2010 paper, the objective of our study was to “learn about” (get to know the) children’s perception of everyday places. The main goal of the project was to define an appropriate tool for the design process. We identified three elements, which were considered to be the most important for child’s identification with environment: home, school, and the journey from home to school. For this purpose, children living in a residential community in Bangkok were surveyed. Contrariwise to the quantitative approach (Neisch, 2010), the concept of Colour – Code Models of space propose a qualitative development of this research – a graphic language which allow to understand the children’s spatial world, the novel way to analyze and present space, useful for educate architects and planners.

Keywords. Spatial network; perception and representation of environment; drawing processing; data analyses; design for children.

1. Introduction

Nowadays, the world of the children and young people is created through

the new technological objects and using virtual people. These factors influence children's life style in the modern epoch and contribute to the loss of social local life and traditional model of relationship and human contact. In this paper, we present the concept of Colour-Code Models of Space. The idea of this tool is to allow comprehending of children's relation with their environment, especially children's perception of town and children's relation with urban and architectural spaces in time of digital realities. It is useful and necessary to have a variety of pictures of the city, because the fact that the urban spaces are different shows that the ways of living in the city can be different as well and we can not consider only one universal way of living in the city. Anyway, beyond some dimensions, it is almost impossible for an inhabitant to spread across the totality of "his city". There are so many faces of the urban life, that we are unaware of many districts, groups or places of our own city. Our research is based on children's perception of environment, which we studied through the analysis of drawings. In a first step, in June 2009 we conducted studies in two Thai schools - one private and one public (located in the suburbs of Bangkok). We employed a quantitative method for analyzing the drawings (Neisch, 2010), however, this method of analysis and the conclusions that we obtained did not seem to be sufficient to achieve our scientist purpose. It was then essential to develop a qualitative method of data analysis - a graphical language (Colour-Code Models) with which it could be possible to connect the elements freely and develop of them an entity of analysed spaces.

To begin with our research, we will first of all situate it in the theoretical context. In the second place, we will develop the concept of Colour-Code Models.

2. Theoretical approach

2.1. PERCEPTION AND REPRESENTATION OF ENVIRONMENT

The studies refer to the psychosocial quality of space, which are considered to be the most familiar areas for the child next to its domicile: the school, the itinerary from home to school, the district. The representation of the environment has at least two functions: it serves primarily to facilitate the location and movement within the major physical environments and, secondly, it provides a general frame of reference for understanding and appropriating this environment. Term "representation" in the broad sense is reduced either to the mental image or memory image (Piaget and Inhelder, 1967). The mental map in the studies of the environmental perception owes a lot to Lynch who

has studied the mental representations of the inhabitants of three cities in U.S. (Lynch, 1960). Categories of elements describing the content of representation were proposed also by other researchers (Appleyard, 1973, Francescato and Mebane, 1973, Beck and Wood, 1976). Exclusively related to cognitive representations formed by adults, these studies used Lynch categories to describe the content of representation studied. While the terminology used in the description of content of representation remained the same as that introduced by Lynch, the interpretation varied according to the approach taken by each researcher. Thus, while Lynch attributed to these categories of morphological and structural characteristics of the city, other researchers attributed to other factors such as level of education, familiarity, age, gender, and practices.

2.2. PATTERN LANGUAGE

Christopher Alexander, architect and mathematician, wrote: *“a pattern language has a structure of a network. However, when we use the network of a language, we always use it as a sequence, going through the patterns, moving always from the larger patterns to the smaller, always from the ones which create structures, to the ones which then embellish those structure, and then to those which embellish the embellishments”* (Alexander et al, 1977). The “pattern” appears to relate to two different levels: 1) the level of the real world (or rather the real world’s perception) and 2) the level of the world of conception. The designer works in a distance from reality - in the abstract space with its own components and its own rules of operation, even if the real world stays always the starting and the ending point of the design work. The two essential components of the world of design are the “problem” and its “solution”. It consists of the definition of a “relationship” that very quickly becomes “Pattern”: term by which we get a more defined picture of the space character of these entities and of their dependency in relation to “context”. Later, “Pattern” is conventionally extended to the problem and its context. Procedures, introduced by the “pattern language” operate at two different levels: the level of production and use. The “pattern language” is considered to be a set of rules of patterns combination and serves as help in programming and in design process. The aim of the “pattern language” authors was to provide the designer a complete methodological tool, which accompanies the start of programming at the end of the design process. No doubt, the “pattern language” functions currently as “a reservoir of information”, but it does not mean that this bank really gives the desirable information to the user. Our objective is to create a language that will take this into account. We will refer to the studies of Ch. Alexander by creation of the structure of the language based on network and sequences.

2.3. CHILDREN AND DESIGNERS

Children's life's spaces and its experience are influenced by the job of architects and urban planners. Planners need to understand better the children's lives and social relationships and have access to and support from child and youth centred policies and practice. Planners have become aware of the need to plan for and with children and young people. Public participation stays in the centre of good planning process and is universally acknowledged as a "good thing" for planners (Freeman, 2005). According to the author, the work on design planning should be based on the will of creation of good environments. It is also important to point that, contrariwise to what we can think, the children use the space in a very broad way. Everything takes place between places, where children live, where they have their activities, where their fellows live, etc. Freeman differentiates three main concepts, which need to be taken into consideration: transport, housing and shopping and speaks about the importance of the correlations between them. He specifies also the requirements of planners: they need to be able to understand how both current and future planning developments, designs and processes impact on children; to recognize the changing and complex nature of childhood, to develop an understanding of children's environmental experiences, to understand what do the children want.

2.4. DESIGN PSYCHOLOGY

We also often refer to the concept of design psychology when we want to create or to define the ideal places. Interesting is the idea of the transformation process of my house' to 'my home' (Israel, 2003). This study illustrates how the concept of design psychology can be prestigious for architectural design. Childhood environments have powerful and lasting effects on people. This is why it is reasonable to use the exploration of the ways of Design Psychology to the design of spaces dedicated to children. It can be suggested that the transition from childhood to adulthood is a period when youth frequently congregate in public places, where they seek to shake off the constraints of home, but do not yet feel comfortable or feel alone in spaces mainly inhabited by adults. (Pooley et al, 2005). Furthermore, young people feel more secure when they find themselves in the urban space. How these spaces are then used and frequented by children? The authors seem to have the same question. *It is likely that young people have always been highly visible in urban areas, but we know relatively little about how the use of urban space by young people has changed over time.*

2.5. UTILITY OF THE CONCEPT

We believe that the development of a graphical tool for analyzing the perception of space can help us to find the answer to this question. Especially, according to the authors, we suggest a factor that has surely changed in recent decades: the personal mobility of children, which is mostly related to commuting as the journey from home to school, shopping, playing or other leisure activities. It seems important to find a way that could help us to study these factors graphically. The concept's of the Colour-Code Models goal is to allow understanding how children perceive their environment, how they perceive a good environment and what are their expectations for it to be. In the future, the Colour Code Models of space could become a tool for public participation in design process or planning.

3. The concept of Colour-Code Models

3.1. FROM SOCIAL NETWORK POPULARITY TO SPATIAL NETWORK'S IDEA

Virtual social networks are very popular and present in almost everyone's life nowadays. If the social networks work so well, why not to create a "spatial network"? The goal of this concept is to allow identifying and charting the important elements, which could be then brought, together and completed by the additional data or information. After such a configuration, it will be possible to read a message of representation and to interact which means analysis of spaces. We refer to the social networks for two reasons. First, they allow the assembly and structuration of predefined information about the profile and the profile user. In addition, this information can be linked to the network, which makes it easier to publish, share and to interact. Consistent with this fact, the new digital reality locks up in the audio-visual images that young people need for communication and information. It is a common opinion that children nowadays communicate virtually, and perceive the world through the new technologies. Since this is a common behaviour, consequently, our concept of Colour-Code Models is based on the principle of the social network, which can talk to children, and it will be able to be used not only to the data analysis but also in the more developed version. In a way, it will be able to be used for public participation in design process. To understand the principals of a social network, we concentrated on functions of Facebook - one of the most popular social network worldwide.

3.2. METHODOLOGY AND DATA

For cutting the urban space and delimiting the profiles of spatial elements,

we defined three elements, which were already detailed at the beginning of the paper and which are the most important elements for child's identification with its town and for its environmental education: home, school and journey from home at school. 'The trajectory studies' function as a method, which allow perception, reading and analysis of exact space. This journey is for children a field of everyday urban experiences. We asked 5 to 9 years old Thai children to answer some different inquiries through several drawings. On the first drawing, children had to draw their journey from home to school. In the analysis, it was then possible to study children's urban environment and equipment. The second enquiry concerned a classification of their relatives by intimacy's degrees, enabling us to study their human environment through symbolic intimacy circles. In the third exercise, children had to draw the plan of their school and differentiate the space where they feel "at home", the space "dedicated to everybody" and the space, which is "forbidden" to them. The fourth activity consisted of sectioning their house inside, sketched with maximum of details, which was the objective to identify space, lifestyle and specific equipment.

3.3. STRUCTURE AND SEQUENCES

The key elements of each enquiry generated a profile of them. Therefore, we create a journey profile, a school profile, a home profile and a relationship profile. All this elements drawn by the children have the profiles, which are connected together within the limits of their author. At this stage, the structure of our tool is based on some particular elements of the space that appear in different sequences. These elements include other elements that define them, supplement them, etc. The profile of the element is represented by a kind of avatar. In the virtual spaces, the avatar is like a second skin and an assemblage of partial objects. In our model, the profile of avatar is a colour synthetic representation of the element drawn by the child. As our concept is the Colour Code Model and in our opinion using colours facilitates the analysis of data, we started using colours in the profiles avatar creation. The examples of avatars are shown in the Figure 1 (school-yellow, home-magenta).



Figure 1. The examples of school and home avatars.

The profile is composed of cropped elements, which define it in the sequences. The Figure 2 presents all profiles with developed sequences corresponding to the data collected for one child.



Figure 2. One child developed spatial profiles.

Generally speaking, the main element's avatar is followed by the original drawing, which is then analysed, cut and used for the Colour-Code configuration. The proceeding of sequences development changes according to the elements specificity. The first line is the sequence of journey. The original picture is redraw and synthesised with the colour charter. The section of journey is created. Thus, we can define the main elements of drawings, examine the spatial connexions and observe the proportions between the elements. The second line is the sequence of school representation, the third that of home and the last one is the representation of the social relationships. Two colours define the sections: 1) the colour of each element and 2) the colour of home or school, which are places, the elements of interest belong to. Using such an approach, it's easy to analyse the data (Figure 3).

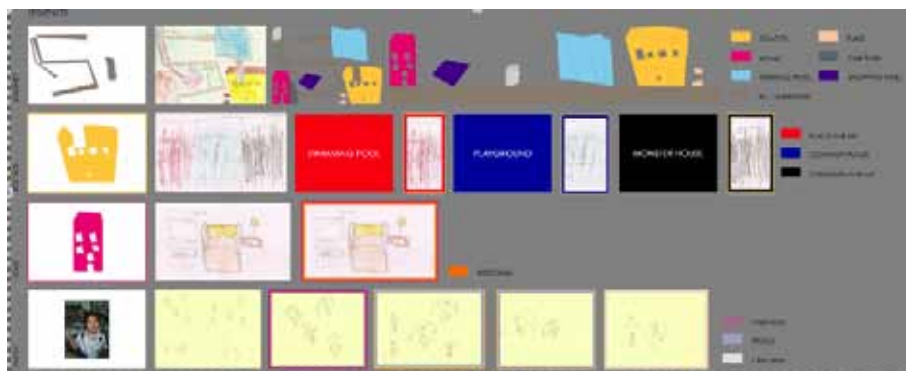


Figure 3. Example of sequences

Allegedly, The Colour-Code Model allows examining the connexions between the elements and their potential configurations. As regards, we are able to analyse the spaces according to users and understanding how they perceive and define the environment.

3.4. NETWORK AND OTHER CONFIGURATIONS

Using the sequences of Colour-Code Models, on one hand, we are able to observe all data that we collected for a child, the importance of each of the elements for the child and the configuration in which the child presents the elements. On the other hand, also the possibility to segregate the elements and create networks seems interesting. All together, the network shows the relations of elements without the configuration of sequences and leads to the complete image of studied places (Figure 4).

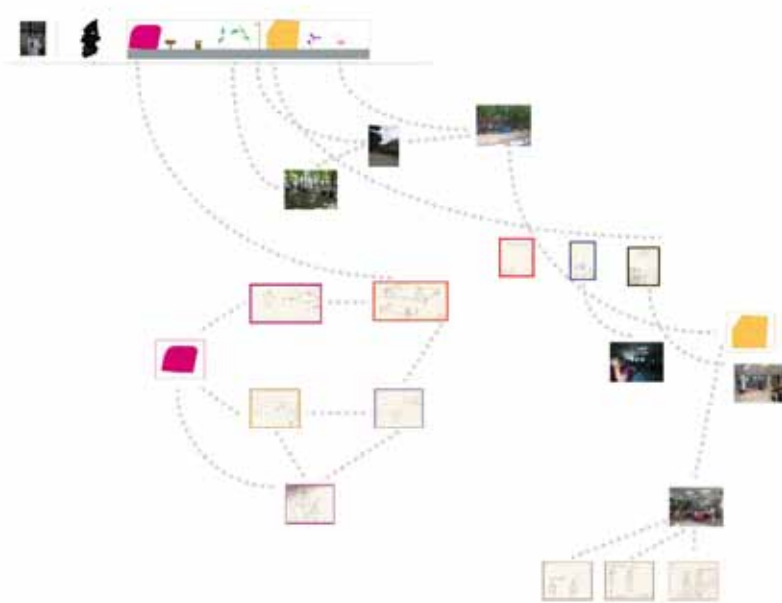


Figure 4. Example of network

An important aspect of our analysis is the possibility to go out of one person sequences or network's configuration and compare spatial elements profiles all together in many different configurations (Figure 5), like the journey representations.



Figure 5. The representations of journey.

This configuration allows having all information together: children's drawings (or fragments of children's drawings), pictures of existing, real maps and mental maps, information about users, reflections of the users, our reflections, conclusions, etc.

4. Conclusion

To conclude, it isn't possible to examine all spatial factors neither by just looking on child's drawing nor by making the quantitative analysis. The configurations of elements picture a lot and allow to link elements between the different surveys (different questions about the perception of environment) as well as to make sequences. It needs to be point out that the child doesn't perceive the space of the city as a one continuous episode but as individual events. Thus the employment of Colour-Code Model allows having an idea of the children's spatial environment. Admittedly, the sequences and network –

allow understanding the child's contact with the city and with urban places and how does the child construct the image of the city. We may outline that these inquiries allow identifying the different spaces where children use to spend most of their time. The results of experimental works made with children make also possible the development of new design tool based on the idealistic vision that children have of their environment. It is then possible to apply to the interface a kind of synthetic childlike image of what is a city, containing information on transports, areas they use to cross, buildings next to which they use to be, etc. Nonetheless, our paper doesn't touch on the subject of results of analysis. The goal was to present and assert the utility of the concept of Colour-Code Model and to situate it theoretical approach.

In addition, we found nevertheless a limitation of this kind of studies - it is not possible to compare the results of our surveys to a spatial reality the drawings referred to. To understand well and be able to use the data collected through the surveys, it seems to be essential to have an idea of the existing reality, without which we are not able to analyse completely the results. Based on this, we realised that it is necessary to add to our surveys questions, which could allow us to place the results on the specific urban space and, in the consequence, to be able to compare them with a visual reality.

The concept of Colour-Code Models it's also a database, a tool of architectural and urban conception that could assist a design projects. So, we need children's drawing for develop this tools, but we need too the maps and pictures of real environment, because all this information form a complex image of children environments perception. In the future, the Colour-Code Models of space could become a tool for public participation in design process or planning.

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PACKING THE “CHINESE BOX”

A strategy to manage knowledge using architectural digital models

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Abstract. The architectural design activity has been transformed due to technological advances in building knowledge management. The research proposed is based on a three years long Ph.D. work on 3D models intended as graphical informative systems, layered according to the “*Chinese box*” paradigm and destined to professionals and researchers in architecture. The applied case study is referred to San Vitale’s church in Ravenna, Italy: the monument was investigated through nested digital models produced by different computer programs. Passing through evolutionary steps identified as *synthesis*, *reduction* and *projection*, the resulting archive lowered its *Complication Ratio*, a numerical value inspired by fractal’s auto-similarity, indicating a recursive modification in morphologies and contents. Models so conceived are qualified as progressive knowledge-based catalogues easily interchangeable and useful to understand how new or existing architectures work. As a result of this approach, representations obtained with surveys, historical chronicles, light analysis and acoustic simulations were composed following gradual refinements: technical data were collected running parallel to bibliographic research, enriching interactive virtual models sprung from a recursive criterion destined to increase the information enclosed into an undivided, lossless, digital archive.

Keywords. 3D modelling; virtual architecture; BIM; CAAD; information database.

1. Introduction

Practitioners and designers involved in building process use different tools and ways to represent projects and ideas: taking advantage of computer models is a consolidated praxis, however different offerings in terms of appli-

cations often leads to errors and omissions when transmitting data between software and operators. Likewise, when developing a new building or studying an existing one, different digital tools need various abstraction to perform analysis or evaluate constructive aspects.

The original idea, or its interpretation, may differ very much from conclusive representations, due to the huge data quantity included into the design process, where contemporary technologies could easily turn edifices into well organized digital archives, but according to different orderings or structures, still not unified and interoperable.

This paper introduces a methodological proposal, expected to make the most of information technology techniques, in order to collect data about architectural environments through a complex digital framework called “Chinese box”.

2. The architecture inside a “Chinese Box”

As Schmitt pointed out (2001), the building process could be generally interpreted as a not completely recursive top-down algorithm, in which the information from schematic design to fabrication, to management and archiving is continuously modified, from conceptual abstraction to a completely different built project, deeply transformed during its evolution.

To use a metaphor, it would be like all models produced during development stages would enter into tunnels, during which they were eventually subject to mutations entirely unrelated to previous or following steps: even if a tunnel passage do not really change what flows through it, it's considered as a sort of black box where everything could happen without complete consciousness by operators.

Getting out of each tunnel, digital models used to formalize buildings' representations and mostly realized with different software, could appear deeply amended if compared to their previous state: they are ready to take the next tunnel, being modified by other operators and getting a further development which will embed again new abstractions into them, while they should be logic emanations of the original idea instead (Figure 1).

Structural analysis programs for example use simplified architectural models or concept digital mock-ups: they introduce variations in order to reach a better performance evaluation, regardless of elements considered important for architectural finishes. The same happens for building energy simulation tools, fire prevention schemes and so forth. The outlined scenario, the tunnel metaphor, reveals how critical is to manage information all over the design process in real fabrication world, since practitioners tend to bend models to their specific aims frequently loosing *ex-ante* compatibility.

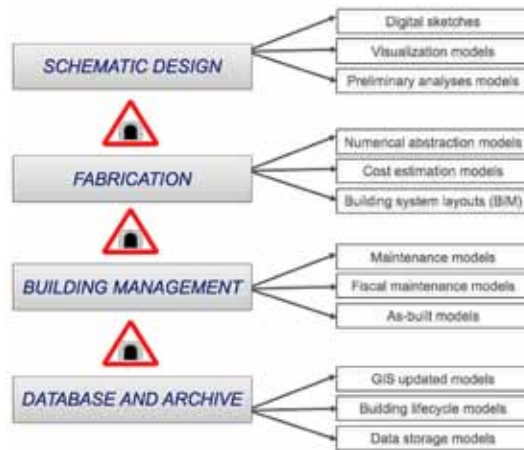


Figure 1. The “tunnel metaphor”: during the building process several applications produce different abstraction of the original idea, leading to not interoperable different models.

As Eastman et al (2008) have pointed out, this is considered a significant issue for cognitive representation. In reverse, the wide dataset management approach suggests how an integrated archive, if properly prepared to collect documents, could limit the loss of information conveyed through passages, overcoming tunnel’s criticalities and transmitting knowledge sequences as they really are, for new buildings and for existing ones.

This is the way to go, creating multi-discipline cognitive catalogues which establish an ordering principle for complexity, hierarchically embedding drawings, pictures, calculations and analytical schemes into an unique global archive: this is the intimate essence of a “Chinese box”.

Even changing the level of detail, knowledge previously acquired remains the same, gradually enclosed in different boxes one inside the other but similar in structure; a “Chinese box” model is a digital collector designed for building actors, promoting a representation of reality from different points of view, as hoped Colorni (2000), most likely moving through *interaction information workspaces* as intended by Liston et al (2001).

According to existing literature, such a comprehensive archiving method does still not exist in architecture, since B.I.M., *Building Information Models*, or C.A.A.D., *Computer Aided Architectural Design* software, can’t fully cover each aspect of cultural design process.

For example, a B.I.M. is too technical to transmit a concept, while a digital sketching program is too simple to produce analytical models to study the building’s performance on its own; probably they can’t even share properly abstraction of the same idea without compromising it.

Furthermore, existing tools for locating building products and assembly models (also known as B.E.M., *Building Element Models*) are still not ready to manage semantic structures, due to compatibility issues of multiple authoring tools. On the contrary, the “Chinese box” paradigm, as intended in this work, is first of all a recursive criterion destined to increase the information level enclosed into an undivided, lossless, digital computer model, making broad room for knowledge representation: results of every software abstraction are collected and made available to everyone in every moment (Figure 2), independently from computer programs used.

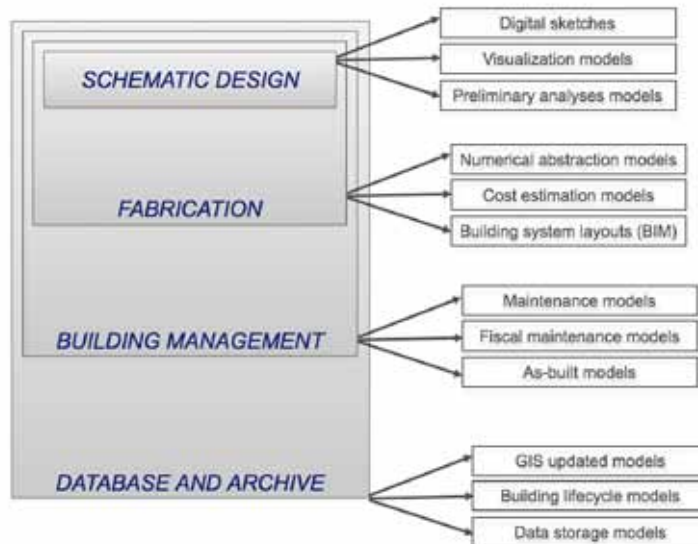


Figure 2. The “Chinese box paradigm”: a recursive criterion destined to increase the information level enclosed into an undivided, lossless, digital computer model.

3. The auto-similar nature of a “Chinese box”

This study was influenced by Lindenmayer’s works on relationships present in plants morphology, where the main structure is completed step by step while growing. Digital models realized to investigate Basilica of San Vitale for example, a following described case study, recursively followed this process stacking up subsequent data acquisition during three distinct phases: *synthesis*, *reduction* and *projection*.

Synthesis is expression of how information can be collected and ideally formalized into computer models, where geometry can be reconstructed for homology in virtual space, gathering heterogeneous data including pictures,

sketches, or tables from surveys: it's the modelling step, referred to morphologies and relations.

Reduction is mainly an oversimplification of the geometric and cognitive model produced, in order to control it in computer memory during analytical calculations. It's a sort of abstraction aimed to perform validations of elements defined during synthesis: an architectural model topologically simplified to allow numerical analysis or energy metering for example, is *reduced*.

Interoperability between analytical tools is the core of this step: I.F.C. format, a way to catalogue building component according to their properties and functions, proved to be the best method to share data between applications without severe corruption.

Finally, with the *projection*, the informative model is presented to final users (architects, engineers, contractors, fabricators, customers) through the medium of technical drawings, visual renderings, performance charts overlapped to digital geometry and so forth. This is, briefly, the display of the design process results.

In a “Chinese box” these operations are cyclically performed so that richer models ease several uses, since they includes materials for a wide number of possible further abstractions. The three-staged scheme is iterative, fostered by several point of view of actors involved in building process: they are in some way influenced by their specific environment, which is surely constantly adapting and changing as Clancey (1997) points out with his *situated cognition*, but following methodological paths in a cyclical way.

This attitude recalls the Sierpinski's triangle geometry, a fractal result of figures recursively repeated. Similarly, beginning from conceptual modelling, every time a significant development in synthesis, reduction or projection is achieved, a progressive complication is added (Figure 3).

In this way the “Chinese box” model evolves, relating its changing to a constant value similar to Hausdorff formulation for Sierpinski's triangle *fractal dimension*, expressed in a specific format called R_C , *Complication Ratio*, obtained from empirical tests in order to evaluate the complexity of a digital model and written as:

$$R_C = \frac{x}{n} \times \frac{\log(3)}{\log(2)} \quad (1)$$

where x is a progress indicator for synthesis, reduction or projection while n represents subsequent development steps.

The Complication Ratio is a number, which consider several aspect of growing such as time to gain data, purposes for whom models have been imagined, level of detail embedded and so on (Figure 4).

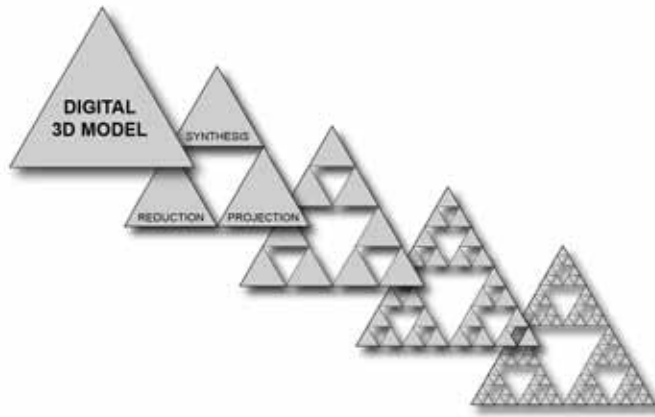


Figure 3. The “Chinese box” digital paradigm recalls the fractal auto-similarity, well presented by the Sierpinski’s triangle: evolving stages of synthesis, reduction and projection can be imagined as self-repeating steps, adding complication to the whole model.

Although it’s very difficult to quantify variables like these, due to heterogeneity of elements which can be inserted into boxes, they can be useful to determine the model dimension. Quoting Mandelbrot (1982) studies on fractal mathematics, the recursive “Chinese box” approach could be nearly similar to a “fragmented geometric shape that can be split into parts, each of which is (at least approximately) a reduced-size copy of the whole”.

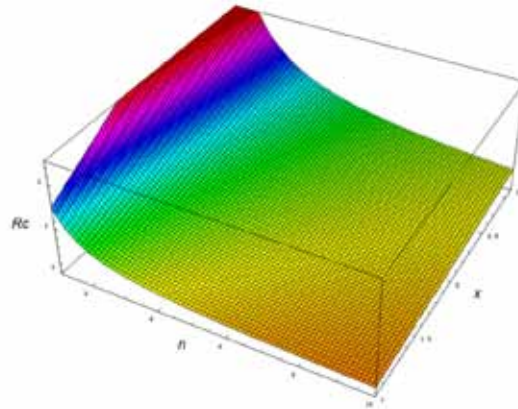


Figure 4. Complication Ratio tends to zero as the digital model evolves.

Without deepening furthermore the R_c expression, not the main subject of this paper, a descending Complication Ratio indicates an increasing level of

development allowing extensive possibilities; it decreases quickly in the early stages of integration and becomes stable later, tending to a gradual asymptotic limit.

4. San Vitale's Basilica case study

As previously claimed, the closer existing technology to “Chinese box” modelling is surely B.I.M.; however it doesn't address issues deriving from existing buildings representation, since it's been mainly developed as a tool for fabrication *ex-novo*. The “Chinese box” on the contrary, was tested in a Ph.D. research on a well-known example of monumental architecture, in order to establish if evolutionary parameter isolated would be effective even surveying a built historic environment.

San Vitale, the elected site, is an Italian church in Ravenna and one of the most important examples of early Christian Byzantine architecture in Western Europe. A photogrammetric survey was realized together with natural lighting evaluation inside the church (Figure 5), while some archaeoacoustic analysis were carried out through derived models, as presented and documented by Knight (2010).



Figure 5. The increasing knowledge about San Vitale was embedded into 3D models, gradually evolving in synthesis, reduction and projection as well, with lower and lower R_c values.

Through several steps and various applications communicating together (Table 1), knowledge about San Vitale was embedded into a growing model, gradually changing its content through synthesis, reduction and projection as well. Presentation of final achievements, the most interesting aspect from the technical point of view, is the clearest expression of what a “Chinese box” is: exploring a simplified 3D digital model (in form of a nested 3D PDF file), it’s possible to focus attention on details which can be delved linking results obtained from previous steps (Figure 6).

Table 1. Steps to collect results from various tools into San Vitale’s integrated model.

Phase	Description	Synthesis change	Reduction change	Projection change	Software used
Step no. 1	San Vitale’s sketchy modelling aimed to prepare a survey and scheduling geometrical data retrieving.	1 (3D model aimed to understand volumes)	1 (geometrical CAD simplification)	1 (paper printings to be used during survey)	Google SketchUp, Autodesk AutoCAD
Step no. 2	Increasing of the level of detail according to information acquired during surveys.	1 (geometry much more detailed after survey)	1 (CAD integrated by photogrammetry)	0 (no variations)	Autodesk AutoCAD, EoS Photomodeler Scanner
Step no. 3	Inclusion of QTVR digital photographic panoramas into the main geometrical model.	0 (no variations)	1 (Model conversion in PDF format)	1 (Model preparation to be explored)	VR Worx, Adobe Acrobat Extended
Step no. 4	Geometrical draping of raster textures in 3D models, to characterize materials and mosaics.	0 (no variations)	1 (Model conversion in texturable primitives)	1 (Digital draping aimed to rendering and movies)	Autodesk Maya
Step no. 5	Oversimplification of 3D models to obtain abstractions aimed to acoustic and FEM lighting simulations.	0 (no variations)	1 (Abstraction for numerical analysis)	1 (Layering of results onto geometry)	Autodesk Ecotect Analysis, Ramsete
Step no. 6	Preparation of a digital integrated archive accessible through several devices (i.e. using PDF 3D format).	0 (no variations)	0 (no variations)	1 (Model presentation via Internet)	Adobe Acrobat, Autodesk Revit

For example, from the main model of San Vitale (which could be even presented on web), photographic VR panoramas from the survey campaign, light analysis of sun rays on interior mosaics or a simulation movie of how could appear the church in VIth century, can be all easily consulted, together with a link to analytical stored files. Patently, those elements were gathered during different phases and managed by different software.

Then procedures followed, historical notes, descriptive papers were collected into the “Chinese box” in form of database, with tables stored inside 3D PDF archives or linked to the models’ components.

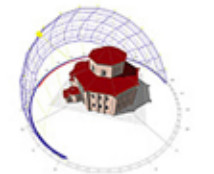
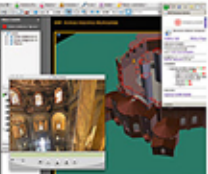
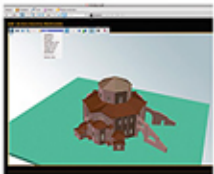
Step n. 1 $x = 3$ $R_c = 1.89$		Step n. 4 $x = 2$ $R_c = 0.31$	
Step n. 2 $x = 2$ $R_c = 0.63$		Step n. 5 $x = 2$ $R_c = 0.25$	
Step n. 3 $x = 2$ $R_c = 0.42$		Step n. 6 $x = 1$ $R_c = 0.10$	

Figure 6. The San Vitale “Chinese box” model: the R_c value decrease as knowledge elements are added to the archive. This behaviour was confirmed by several tests, referring to new and existing buildings during survey or fabrication. The x indicator expresses how many variables (synthesis, reduction or projection) change their contribution during selected step.

5. Conclusions

Construction is a collaborative endeavour, a complex process in which concurrent goals are to be fulfilled, as Gero and Kulinski wrote (2000). The “Chinese box” is a tool aimed to arrange in concert and destined to architects, engineers, researcher, contractors, fabricators and so on, just to make knowledge sharing easier. It’s not a computer program, it’s a human activity which

involves an inevitable process of change in methods applied to architectural-related disciplines.

In years to come, the conscious use of existing tools will contribute to the spread of high-profile building components, generating a great flexibility and variety in methods and types of construction. Optimistically, this process will produce less building documents, containing less errors, avoiding time wasting and allowing fabricators to arrange late changes, reaching higher productivity.

On the other hand, project's standardization due to digital tools is a danger to keep in mind: for this reason, high technologies and proprietary software should be introduced into the design chain only in specific points, favouring the choice of interoperable algorithm and devices. This is the crucial point which promotes the "Chinese box" modelling as an alternative to pure B.I.M., as it can't successfully integrate all the cultural work flows in a coherent manner, allowing actors involved to analyze in a deep way architecture during the whole building process.

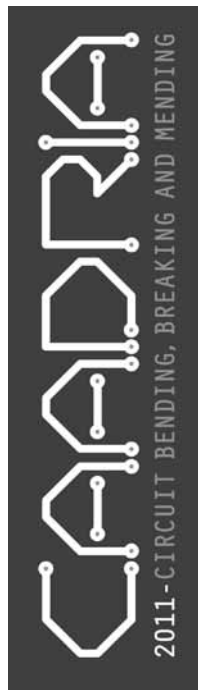
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DESIGN INTELLIGENCE AND AUTOMATION



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69.	Using domain specific languages in the Building Information Modelling workflow	731
	<i>Ruwan Fernando, James Steel and Robin Drogemuller</i>	
70.	Digital manga depiction	741
	<i>Marc Aurel Schnabel and Yingge Qu</i>	
71.	Structural form generation using interactive genetic algorithm	751
	<i>Weixin Huang, Weiguo Xu and Tao Wang</i>	
72.	Daylight and energy in the early phase of architectural design process: A design assistance method using designer's intents	761
	<i>Mohamed-Anis Gallas, Didier Bur and Gilles Halin</i>	

USING DOMAIN SPECIFIC LANGUAGES IN THE BUILDING INFORMATION MODELLING WORKFLOW

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Abstract. The design of architecture, in practice, entails the collaboration of many disciplines each with their own set of tools and representations. Building Information Models aim to support interoperability between these disciplines. However current implementations require a lot of manual work involving translating parts from the various specialised descriptions to the common model format. Domain Specific Languages are a development from Information Technology that defines a mapping from the concepts used in one discipline to those used in another. In this paper, a workflow incorporating the movement between specialised languages and a central model is described. The central model is structured using the Industrial Foundation Classes (IFC). The motivation for elaborating on the interdisciplinary workflow is the desire to create a more iterative process without the need for the manual recreation of models. While it is difficult to have a description or language that contains all the information of all the disciplines, this research demonstrates how the IFC schema acts as a pivot not just between data sets, but also between concepts expressed in different representations thus giving from analysis to design.

Keywords. Building Information Model; BIM; domain-specific languages; lighting; spatial planning; parametric modelling.

1. Introduction

In software development, a domain-specific language (DSL) is a smaller language dedicated to a particular problem domain. Deursen et al offer the following definition:

A domain-specific language (DSL) is a programming language or executable specification language that offers, through appropriate notations and abstractions, expressive power focused on, and usually restricted to, a particular problem domain. Deursen et al (2000.)

In this regard domain specific languages are not at all new – architects use a variety of media to explore different concepts from orthographic drawing to physical models, engineers use mathematical abstractions and simulation models. Many computer-aided design tools allow for scripting or *macros*, to enhance workflow by grouping together repetitive sets of commands – these in fact form a small ‘private’ DSL used by the modeller.

An important distinction should be made between ‘domain’ and ‘discipline.’ The Architecture, Engineering and Construction (AEC) industry has evolved to differentiate between disciplines such as landscape design or electrical and mechanical design. A domain can be shared between several disciplines such as the domain of ‘spatial reasoning’ or ‘geometry’ or several domains can be used within a single discipline e.g. in HVAC engineering, Computational Fluid Dynamics and Duct Layout modelling are two distinct domains. Domain specific languages and modelling tend to use higher-level abstractions than a general purpose modelling language. For example consider the scripting language in Computer-Aided Design (CAD) software such as ‘*Rhinoscript*’ in comparison to a general programming language such as ‘*Java*.’ Thus a DSL requires less effort (for the human modeller) and fewer articulations in at the low-level aspect of computation.

Building Information Modelling (BIM) is fast gaining popularity in the AEC industry. For an explanation of BIM or its use in the industry, several authorities are available e.g. Eastman (1995). Because BIM uses three-dimensional geometric modelling as well as the representation of meta-data, it is an ideal way to move information between groups. Older forms of communication such as 2D drawings are prone to misinterpretation – and require remodelling of geometry when tasks such as simulation or visualization are needed. The largest attraction of BIM is therefore, that it makes possible an integrated approach to design – different disciplines can modify or analyse a model during its inception in opposition to the serialised approach of moving drawings from one group the next only after completion.

The formalisation of BIM that this paper elaborates on is the Industry Foundation Classes (IFC). These represent an accepted open standard that is supported by most of the major CAD vendors. Most other BIM descriptions are proprietary or limited to a single vendor. While successes have been reported in many cases with the use of IFC, there is lot of work that needs to be done with regard to connecting models to analysis and domain specific software.

For a description of how the IFC schema operates see Steel et al (2010). The main idea that this research proposes is that the building information model act as a pivot, being mapped to by different domain specific languages. The complexities and issues of this are discussed.

2. Domain-specific languages: Theory and use in the AEC industry.

At a very simple level, a DSL can be implemented through inputting text instructions in a manner similar to using *macros* available in many software systems. In this context however, it is more likely that the instructions that are sent to the computer will be in the form of interactions with a GUI (Graphic User Interface.) Almost all of the most popular CAD and BIM software available allow for extension using powerful general purpose languages.

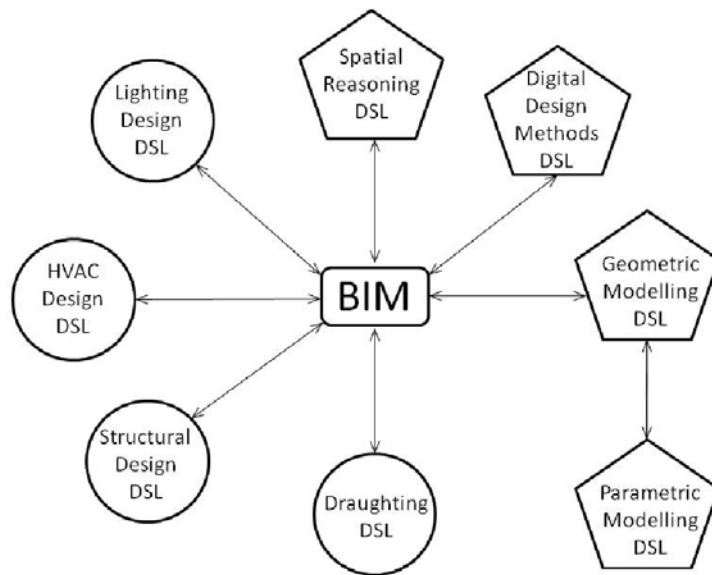


Figure 1. Different domains with a central BIM

Figure 1 isolates several common domains that are present within the architecture and engineering disciplines. The domains that are enclosed in a circle are particular to a discipline while the domains within pentagons are shared

amongst several disciplines. In the field of software engineering, using domain-specific languages in order to describe software systems, stretches back to the early 80's and the development of so-called fourth-generation languages (4GLs), but has garnered more attention recently – Fowler (2010). The essential idea is that, rather than requiring the designer to express their design model in a general-purpose language with concepts at a lower level abstraction, they be given a language whose concepts are a closer to those in which they think about the problem and solution space. Typically, these domain-specific languages can then be mapped to lower-level languages, in order that they are subject to more general-purpose tools, either to analyse the design, or in the common case for software engineering, to actualise it into a running system. The DSL approach is particularly useful when dealing with diverse domains, where the lexicon of the designer is removed from that of the lower-level languages they might otherwise be forced to employ, as well as in situations where different domain experts need to work on a unified system (Hessellund et al, 2007). There are a number of possible approaches taken to the development of a domain-specific language. The simplest is through the use of *macros*, whereby a domain-specific concept can be encoded as an in-place expansion to a number of concepts in the lower-level language. This approach, common in languages such as C++, has the advantage of being easy to implement and evolve, and of allowing the user to mix and match concepts from the DSL and the lower-level language, but requires the DSL to have a strong structural similarity to the lower-level language. Another approach is by embedding the domain-specific concepts and syntax within a general purpose language. This is common in languages such as Ruby or Lisp, and also has the advantage of giving the designer the ability to use concepts, but provides more support for domain-specific syntax than the macro approach. A third approach is to use more heavyweight tools in order to design the DSL and its supporting tools from the ground up. This allows the DSL to be structurally independent of any lower-level language, and thus greater flexibility of form and of syntax, but requires more effort to provide tool support and a mapping back to a lower-level language, although this has become dramatically easier with recent advances in language- and model-driven engineering. Given the diversity of disciplines used in AEC, and for reasons stated earlier it is this third approach that offers the most promise when looking at DSLs for the Architecture, Engineering and Construction industry.

The lower-level language serves an important role in the use of domain-specific languages. It serves as the pivot point where domain-specific designs can be integrated, and exposed to tools for simulation or analysis, thus obviating the need for the DSL developer to develop separate tools for the design model

in its domain-specific form. In this paper, we propose that the most appropriate language to serve as a pivot in the application of the DSL approach to the AEC space is that of the Industrial Foundation Classes. One of the common criticisms of IFC is that it offers too wide a variety of modelling constructs, but this can serve as a strength when it is employed as a pivot language for the integration of heterogeneous domain-specific design models. Also, as the significant open standard in the digital design space, IFC remains one of the best conduits for connecting domain-specific models to analysis tools.

The benefits of a DSL approach to design in the AEC space require that there be a sound link between the domain-specific language and the pivot language. To this end, we are exploring the use of model transformation languages, which are becoming a popular tool for mapping between different modelling languages within the model-driven engineering community. There exists a variety of open-source tools [Jouault, 2006; Steel 2004] for describing the concept-to-concept mappings between modelling languages, and for automating the conversion of their models. Since the mappings between languages can vary greatly, we anticipate using different model transformation languages for the different domain-specific languages.

3. Parametric modelling: Lessons for object-oriented programming

Flexible modelling is at the foundation of the workflow being explored. Without the ability to make changes rapidly, an integrated approach becomes unfeasible with the time constraints set in normal competitive practice. While many different opinions and definitions exist with regard to what constitutes parametric modelling, the definition used here is that in a parametric model, the geometric properties of any CAD object can be expressed as a function of other objects or values. For example if a beam were to span between two walls, bringing the walls them closer or further apart would change the length of the beam to follow this constraint. A more advanced way in which parametric modelling can be articulated is by taking an object-oriented approach. Many lessons can be learnt from the evolution of object-oriented programming concepts and methods. Some fundamental concepts used within this field are inheritance, polymorphism and encapsulation.

3.1. INHERITANCE

Inheritance is the act of one object inheriting properties from another object. An object that cannot be instantiated but only inherited from is described as '*abstract*.' This principle is illustrated in Figure 2. The top-left image shows an abstract 'jig' for a floor slab. This object defines a planar polygon and a one

dimensional grid. This abstract class can be inherited from and instantiated in several ways – the first one given as a simple slab (the IFC scheme carries the object ‘IFCSLAB’ within its object set) the next two are assemblies of beams and the slab. The beam definition is replaceable as long as certain criteria are met. In this case, that it be defined by a planar polygon and extruded along a straight line.

3.2. ENCAPSULATION

Along with inheritance, an important concept that follows is one of encapsulation. This aspect of object-oriented programming controls the level of access of different properties of the objects. In the floor slab example, the polygon that defines the shape of the floor might be constrained to being planar by ‘hiding’ the Z-coordinate of the points or lines that define the shape. Thus avoiding any scenario which a non-planar polygon is given. As the floors become more complex, more properties are made variable – with the fourth floor example, the properties of the I-beam that supports the floor become part of the assembly.

In systems involving the manipulation of complex objects, it is imperative that the methods and functions that operate on these objects are easily accessible when dealing with them. One popular method is to release these objects with their functions within the same definition. For example if the area or longest dimension of the polygon that defines the floor was needed by another operation or object, the tasks of getting this data is simplified when it is held by the object itself.

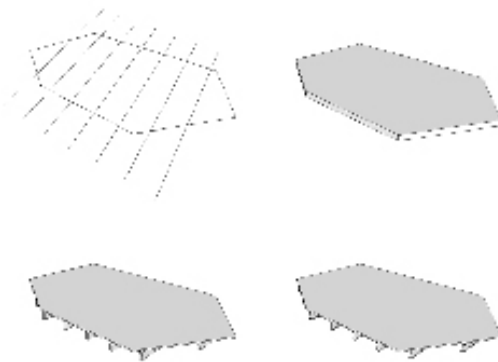


Figure 2. Floor system, inheritance from an abstract class

4. Case studies

4.1. LIGHTING DESIGN

The field of lighting makes a good introductory study in that the simulations performed by lighting analysis software such as Radiance is largely made up of only three parts. The first is the geometry of the objects in the scene, the next being the material properties of these objects and the last being luminaire definitions. The IFC scheme itself holds several lamp and luminaire definitions, so the mapping to a lighting analysis package is a straight-forward task as illustrated in Figure 3. The language used by lighting designers include words such as ‘*illuminance*’, ‘*lux*’, ‘*glare*’, ‘*daylight factor*’ and ‘*emissivity*.’ A unit of measure common to this field as well as of interest to energy efficient design is that of the Watt. Therefore this becomes a unit that can be used as a baseline to discuss the benefits of different variations.

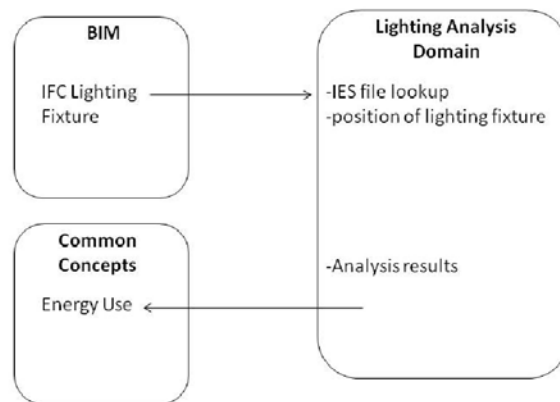


Figure 3. The lighting design domain

4.2. SPATIAL REASONING

A serious issue with a lot of BIM-led projects is the amount of data that is present in the files. This can cause long waiting periods for the model to be visible in 3D. The simple act of being able to select what should be sent to the graphics pipeline has enormous benefits in reducing the waiting time for the model to be made visible. Many CAD and BIM packages allow for the

viewing of layers – differentiated by pre-set or customized object categories. An example of a fragment of a DSL used for spatial reasoning could appear as: *'show levels 2-3, structural, and lighting'*. This would only send the selected levels to the pipeline in that view without having to manually switch on or off layers.

4.3. HVAC AND STRUCTURAL DESIGN

The Heating, Ventilation and Air-Conditioning discipline is interesting in that the common definitions used are not just geometry but also topology. It is common to describe duct layout systems using graphs – nodes, edges and weights. Ductwork layouts can be complex entities to describe procedurally in this regards as the room shape can shape the topology of connections – a weakness of parametric modelling software. In this case iterative solutions are sometimes better. Brahme and Mahdavi (2001) give a solution to the problem of formalising duct work dynamically with regard to topological changes. As environmental services represent a large amount of the buildings total energy use, it should be noted that interaction between this domain and energy analysis is a critical one.

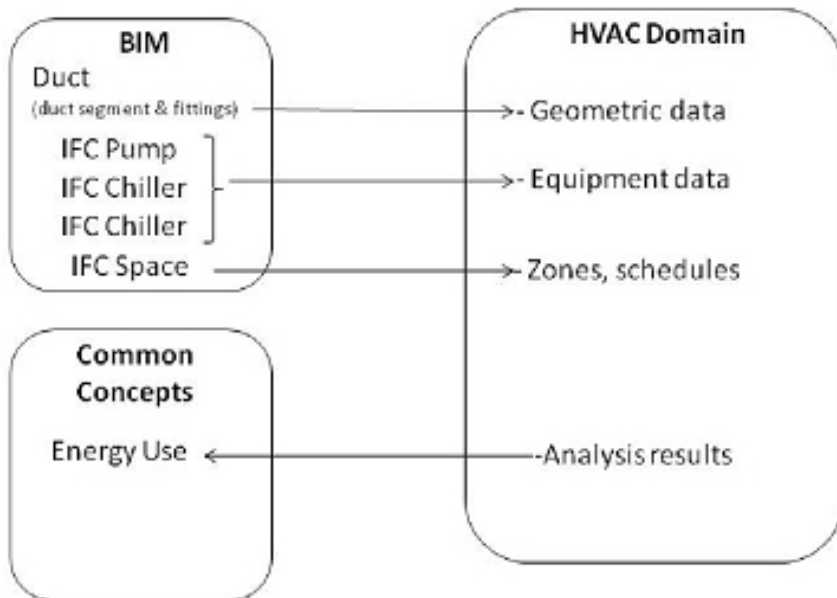


Figure 4. The HVAC domain

4.4. GEOMETRY

Geometry is a field common to all disciplines and is an important domain holistically. A more specialised DSL within geometry is that of parametric modelling, the importance of which was discussed in the previous section. The DSL for this domain, capture important relationships in having the objects adjust to different scenarios. While many texts exist entirely on this topic (i.e. Lee, 2006) for the purposes of the main ideas presented in this research, the following points are made:

- It should be possible for a BIM capable system to describe an object procedurally so that it can be rebuilt according to difference parameters.
- Objects should have multiple levels of representation appropriate to levels of detail visible.
- It should be possible to link the parameters of an object to that of another to associate the properties of objects.

Flexible geometry manipulation lies at the very foundation of creating an iterative process.

4.4. GENERATIVE DESIGN

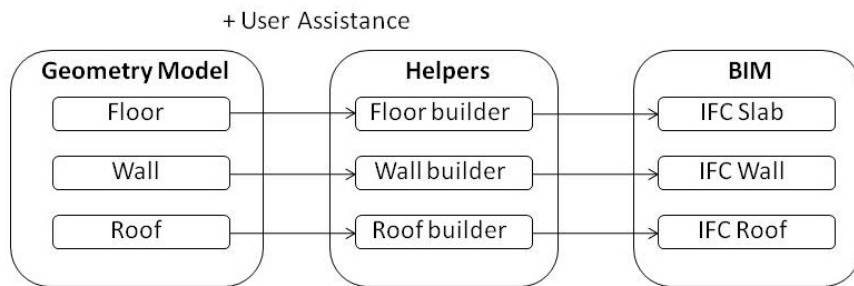


Figure 5. Creating a BIM from a geometric model

This topic was chosen for variety as it does not fit into practice, but rather, academia. The use of BIM at the level of study is less popular as most BIM software packages do not give the freedom of free-form modelling packages. There is however benefits to using BIM even at the study level – the most pertinent one being the use of analysis tools. The most important DSL linking these two fields is a language allowing for objects to be described by geometry alone – and then having their BIM definition written out. A set of ‘helpers’

that formalise ‘shapes’ into BIM objects - floors and walls – can help move between such tools and building information models. More sophisticated design techniques are being developed in many diverse AEC related fields – for example in HVAC, Beghi et al (2009), show the use of genetic algorithms to manage the designing HVAC systems. If such systems make use of BIM as a pivot, researches would have easy access to well-developed modelling and visualisation systems.

5. Conclusion

While BIM has great potential and is quickly becoming the norm in the AEC industry, there are still many barriers to overcome. The most important of these, being able to create a feedback loop between analysis and model adjustment. As an activity, design relies on being able to work with an intuitive understanding of problems and their possible solutions. It is important to be able to break a problem into parts, but also to be able to work both holistically and in a specialised manner. The closer representations come to the conceptualization we use to solve problems, the easier it is to articulate them. In this regard, domain-specific languages are a powerful way to build on knowledge and to build systems on top of other systems.

Acknowledgements

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DIGITAL MANGA DEPICTION

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Abstract. Same as rich colours in a painting that deliver the artist's thoughts and ideas, the variety of textures and patterns in sketches gives drawings different significance. Using rich sets of texture screens to represent chromatic images, the visual perception can be preserved by using the texture pattern verities. In our work, we present a harmonic representation from chromatic space to textural space, to generate architectural sketches and their details, including colours, textures, and tones. We present a rendering appearance for the communication of architectural design akin to Japanese cartoon depictions. In our results we demonstrate successfully that our method generates sketches from architectural images that preserve architectural key-elements, such as surface or material properties and simulate a chromatic correct perception. This allows for novel depiction and story telling in architecture.

Keywords. Manga; sketching; story telling; non-photorealistic rendering; multidimensional scaling.

1. Introduction

Colour and texture are basic elements of what we perceive and comprehend in a drawing. The diversity of colours imposed on a painting expresses artist's thoughts and ideas, which accordingly influence our visual experience and appreciation of the artwork. Similar to the function of chromaticity variance in colour paintings, monochrome sketches offer variations in textures and tones for the same purpose, subsequently the act of sketching allows for its own experience and interpretation of spatial arrangements (Goldschmidt, 1991). Digitally aided sketching either provides invariant patterns or requires user hand-drawn input for pattern variations. As seen in Figure 1(b), the computer generated diagonal hatching provides no distinguishability to the colourful content in the original image Figure 1(a).

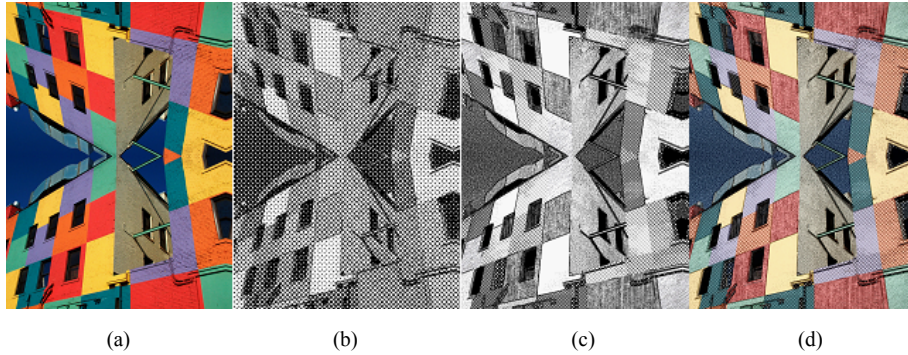


Figure 1. Generation of a computer aided sketch from a real photograph (a). Transformation using commercial software (b) adopts hatching technique and present uniform textured result. Our results (c) and (d) preserves colour distinguishability; texture similarity; and tone

In our work, we explore the *harmonic depiction* of chromatic and texture depictions that refer to creating a suitable interpretation of the internal relationship of colour plates using texture variations to provide a pleasant visual perception of both colours and textures of a computer altered drawing.

We introduce novel depictions of images that provide an alternative rendering of a colour drawing/image into a harmonic explanation by using texture patterns (Figure 1(c)), and an extensional blending using both colours and textures (Figure 1(d)). This novel representation is especially useful in context of architectural depictions. Given an arbitrary colour image of an architectural arrangement, our computational method can instantaneously transfer the input into a bi-tonal multi-screening texture representation. Since architectural design is rich in details and elaborated in high levels, the process of creating an adequate illustrative sketch becomes even more complex. To speed up the production time of drawings, some artists already employ computer techniques to convert images to hatching effects, using techniques such as ‘half-toning’ or ‘hatching’. However, these digital methods produce only monotonous patterns and unsatisfactory results that are not in line with the rich expression of colour graphics and elaborated architectural details in sketches.

The graphical quality of our work is unique in its elegant use of rich set of screens, and tidy and fine drawing styles. This novel way of visual communication of both chromatic and textural features provides another realm for representing architectural drawings or photography, being real or virtual. Although sketched drawings depend on pure black and white (B/W) patterns and lines, or is bi-tonal representation, it is still possible to perceive the variety of textures or materials of the surfaces of buildings. During the screen-

ing process artists can lay multifarious screens to express different semantics. Here the 'screening' refers to the process of laying pre-printed b/w patterns over a certain area of the image. Screens are selected not solely according to the chromaticity, or tone, but also according to texture, material property, shading or even function of the underlying architecture that is being depicted and expressed.

Our technique can deal with an arbitrarily complex image or colour palette. Rich sets of texture patterns/screens are employed to represent the original image with the goal of preserving three key-factors of graphical representation: *chromaticity distinguishability*, *texture similarity*, and *tone similarity*. While the tone is preserved by matching the density of the tone with the one of each texture pattern, the core contributions of our method is the preservation of chromaticity distinguishability in a harmonic way; in other words to keep the perceptual distances between chromaticity by using variety of patterns. To this end, we develop a novel colour-to-pattern mapping based on the Multi-Dimensional Scaling (MDS) technique (Cox and Cox, 1994). As shown in Figure 1(c), our result preserves the original tone, while differentiate the chromaticity of the original image. Our system allows designers to interactively control and fine-tune their results.

2. Depictions

2.1. ARCHITECTURAL SKETCH

Architectural drawings are a universal convention that uses screens, symbols, hatches, line-types, -styles and -widths to describe elements of a design, its properties, functions or materials. They are filled with represented knowledge and key information for a specific composition. In addition to that, architectural drawings are flexible and allow the creativity of individual architects to influence the overall style of the screens and their variations. In contrast to this, Computer Aided Architectural Drafting (CAAD) typically has no personal style and depicts neutrally norms of the architectural, engineering and construction (AEC) industries.

Since the 16th century the tradition of drawing as an act of designing freed the architect from working on site and subsequently design became also an intellectual discipline engaged in the plane of paper. Goldschmidt (1991) argued that the architectural sketch is a mode of visual thinking and communication, which is crucial to a conceptual framework of the depicted architectural design. Despite the advancement of digital media, there remains a certain quality of a hand drawing and the architectural sketch remains the predomi-

nant medium of designing, communicating and construing. It incorporates abstraction, fuzziness as well as clarity and sharpness. As that the expressions of lines and hatches themselves become the objects of meaning and interpretation. A sketch explores from overall relationships to fine resolution of detailed attributes of the depicted design. In order to make the communication of architectural space more precise the drawing makes use of graphic modifiers to convey information that go beyond the pure outlines or dimensions of the spatial arrangement (Robbins, 1994) (Figure 2).



Figure 2. Depiction of Jeremy Ham's Residence (clockwise from top): Computer-rendering, photo of actual building, architectural manga from photo and two manga-depictions from computer renderings using different hatching and screens and hand-sketch by architect.

The architectural sketch that is similar to an artistic drawing uses various graphical elements and drawing techniques to express visual clues of the depicted scene. Texture materials can be rough, bumpy, slick, scratchy, smooth, silky, soft, and others, while having various patterns. Painters and sculptors who work in the realism style imitate natural surfaces and textures. The artist paint textures to create an illusion. In the same way, the architect can use the texture

to difference a place to other, and create in them different sensations. Subsequently our computational representation is able to re-represent these fine nuances of hand sketching that differ greatly from computer generated renderings or ISO (2002) conventions (Figure 2).

2.2. ARCHITECTURAL MANGA

Manga, a popular Japanese comic art form, is increasingly becoming known around the world. Manga are used to develop a storyline that engages the reader not only with the visual aspects, but also other sensorial feelings. The graphical quality is unique in its elegant use of rich set of screens, textures, tidy and fine drawing styles. This specific way of visual communication provides a novel realm for representing architectural drawings or photography, being generated real or virtual (Figure 2). Architecture is subsequently not only represented through its factual dimensions of length, width and height, but is extended to intangible sensorial realms.

Our specific method allows architects a novel way of storytelling and depiction of their designs, from a wide overview to rich details. Plan, section and elevation are fundamental parts of architectural communication. Many methods have been explored to express architectural designs in other ways of depictions. Japanese comics in particular use strong expressions and rich set of drawing details to engage with the readers with their stories. Hereby the protagonist acts in front specific architectural settings. Our method elevates the background—the architectural settings—to the protagonist and to the foreground. Subsequently the storyline centres around the architectural design.

3. Overview of the Harmonic Textural Drawing System

Richness preserving manga screening offers a solution to generating bi-tonal manga screening for an input colour image (Qu et al, 2008). Their goal is to preserve the visual richness in the original photograph by utilizing not only screen density, but also the variety of screen patterns, during manga drawing. Base on this work, we develop a system to draw architectural depictions using variant textures and level of abstracted lines. Our system consists of two major components, screening (texture rendering) and line drawing. For the screening process, we use mathematic schemes, the MDS (Qu et al, 2008), to map between the colour space and the texture space, by preserving the relative distance among each individual space meanwhile. In this way, we build the harmonic relations for texture variances, in terms of the corresponding colour perceptual difference. Our aim is to provide a mapping scheme for the texture rending with the goal of chromaticity-difference preservation, so

that the textural rendering has a harmonic appearance with the original colour image, in visual perception context. For the line drawing part, we propose a line importance model to rank each line. With this ranking, architects can control the detail level of lines needed in their architectural drawing, via a simple threshold.

3.1 HARMONIC TEXTURAL DRAWING

The main objective of screen matching is to preserve the rich content of the original reference image. Here, we aim to preserve three classes of contents including tone (or luminance), texture and chromaticity distinguish-ability. Therefore, the screening method consists of the following three steps:

- *Texture-based matching.* As illustrated in Figure 3(a), segments containing apparent texture are first matched with screen patterns based on the texture similarity. This guarantees the pattern features on the architecture will be remained in the B/W manga drawings. To do so, we choose the Gabor wavelets texture feature to capture the representative feature in each regions of the input photo. Next we compare the feature vectors between the input photo and the features of each screen in the screen library. The most closest one from the screen library is then chosen to render the target region area. Figure 3(a) shows an example matching of the textured wall with the screen “bricks”.
- *Colour-to-pattern mapping.* The unmatched regions are mapped to different pattern types with the goal of maintaining colour distinguishability, via a colour-to-pattern mapping. We use MDS to map between the colour space and the texture space, by preserving the relative distance among each individual space meanwhile. In Figure 3(b) we assign the bottom patterns to the above colours. Subsequently, we assign red and orange regions with two close patterns, as they are closer in colour. While blue regions will be screened with a substantially different pattern. In other words, we maintain the relative distance among colours after mapping to the screen space.
- *Tone matching.* After the first two stages, each region has been assigned a screen type. The final step is to perform a tone matching by selecting the appropriate screen density. We match the overall greyness of the screen with the average luminance of the segment (Figure 3(c)).

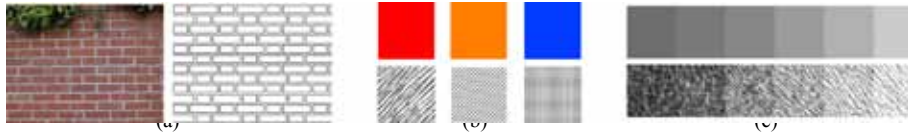


Figure 3. Objectives of the screen matching: (a) Texture preservation, (b) chromaticity distinguishability, and (c) tone preservation. In (b), we assign the red and orange regions with two close patterns in below, as they are closer in colour; on the other hand, the blue region will be screened with a substantially different pattern.

3.2. LINE DRAWING AND ABSTRACTION

Edge detection extracts lines purely based on the intensity gradient in the image. No attention is paid to the importance of a line. In many cases, edges obtained by automatic edge detection methods are far from satisfactory as demonstrated in Figure 4(b). However, lines drawn by artists are usually tidy without being too crowded or chaotic. Some artists intentionally omit many detail lines in order to maintain the tidiness and abstraction of the drawing. However, structural lines are retained, meaning that some lines are more important than others, and these lines usually form the main structure of a building or spatial arrangement. Therefore, we propose a model to measure the importance of a line and unimportant lines are filtered out by adjusting a single threshold.

We begin our line formation from the edge detection on the original image. We adopt an improved edge detection method (Meer and Georgescu, 2001) that shows the ability to detect consistent results, even on weak edges.



Figure 4. Edge detection result: (a) Original image (b) Edge detection result.

To tell structural lines from details, the key is to determine the importance of a line, so that a high importance value indicates structural lines while lower value indicates detail lines. Architects usually first draw the long and straight structural lines during sketching. The short and curly lines are drawn at later

stages or even omitted (Cheng, 2006). Hence, the curliness and the length of lines suggest its importance. We also believe that lines associated with the major segment in the photograph should be more important. This suggests four factors are to be considered, the length, the curliness of a line, the size of largest associated segment, and the visibility value. Figure 4(b) shows the unstructured edges from the raw edge detection result. With the proposed line importance model, we can generate the lines with a desired degree of abstraction to simulate architectural drawings with different level of complexity or line abstraction. Figure 5 shows five different levels of abstraction of lines.



Figure 5. Level of line abstraction controlled by the line importance values.

4. Results and discussion

A variety of input examples, including architectural photographs, colour drawings and artworks of spatial descriptions have been testified with our automatic drawing system called 'Mange-Me' {www.manga-me.tk}.

In Figure 6 we show an example that demonstrates the chromaticity distinguishability of the proposed system. Unlike the monotonous pattern appeared in the halftone result in Figure 6(b), the colour variety in the input photo is well preserved by with screen variety as shown in 6(d). We used five screens to represent five distinctive input colours (Figure 6(c)). By blending our result with the input image, such result illustrates the faithfulness of our textural presentation and emphasizes the relationship of building elements with each other as well as to the whole architectural design.

This is particular useful to communicate large concepts that feature a variety architectural topologies, material, form, details as well as additional abstract information, such as design intent, light qualities, movement, and depth. Subsequently texture rendering can enhance the communication of architectural representations. Our technique allows designers to abstract spatial relationships while at the same time preserve properties of material, surface or detail.

Our technique allows for the development of a unique architectural design communication that goes beyond graphical depiction of technical drawings moving to story-telling using the particular style of comics. Figure 1(d) dem-

onstrates a novel drawing style by blending the texture rendering with the colour rendering. It lifts the drawing in both semantics.

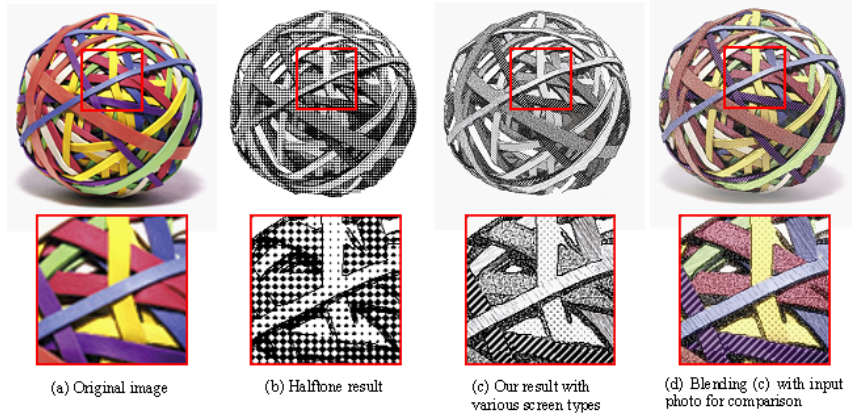


Figure 6. Unlike the monotonous pattern in halftone technique (b), the colour variety in a colour input photo or drawing will be well preserved with screens variety, as shown in (c), by our colour-to-pattern mapping (d).

Despite Stacey and Eckert's (2003) findings, it is commonly understood that sketches express an added value to the communication. The strengths of architectural sketches often lay in the ambiguity and abstract translations of the original depicted or imagined spaces and designs. Our technique allows architects to blend from a photorealistic to an abstract depiction of architecture using a distinct expression of akin to the Japanese tradition of manga.

5. Conclusions

We have presented a novel drawing technique for harmonic texture drawing with colour drawing that utilize texture drawing techniques, and provide an optimal screening scheme by using multiple screens and level-of-detail line abstractions. The high dimensional screens enable the texture and tone preservation, as well as the harmonic chromaticity representation of the depicted original (Figure 7). The system is efficient and convenient in use in architectural design and communication. We demonstrated how the specific textural drawing technique can be utilized to design and communicate spatial arrangements. The intersections of manual and digital instruments mirror the working styles of architects, who deal with a variety of realms, instruments and stakeholders. Hereby this harmonic texture and colour drawing aids not only users to understand larger architectural concepts, properties of form, material, light, etc, but also story telling, developing a narrative (Ng et al, 2006), and e.g.

consultancy of professionals (Schnabel and Howe, 2009). Laypersons easily can access the architects' intention of design and function.



Figure 7. Our manga-style depictions properly preserve the multiple textures and colour-distinguishability of the original urban scenes.

Acknowledgements

The authors wish to acknowledge the software 'manga-me' {<http://manga-me.tk>} by *MangaTech* {<http://mangatech.tk>} a development by TT Wong, PA Heng and Y Qu., CUHK. A free version is available as an *iPhone-App*. More images at the above URLs.

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STRUCTURAL FORM GENERATION USING INTERACTIVE GENETIC ALGORITHM

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Abstract. Structural form design could be considered as a bi-objective problem which should satisfy both the efficiency criterion of structural engineering and the aesthetic criteria of architects. This research tries to introduce Interactive Genetic Algorithm (IGA) in the problem of structural form design. It combines the structural analysis performed by computer and aesthetic evaluation by architects into a bi-objective IGA process, in order to generate structural forms which are preferred by the architects and at the same time structurally optimal. In this research, the structure generated consists of two kinds of members, truss and beam. Generation and evolution of structure is based on a triangular element composed of several members. Through experiment of the IGA structural form design system, it is found the structure forms are optimized as the evolutionary process proceeds, and the aesthetic preference of architect is also transferred from generation to generation. It is also revealed that the two criteria have mutual restrictions, which resulted in compromised results.

Keywords. Bi-objective optimization; structural form; interactive genetic algorithm; subjective evaluation.

1. Introduction

Architects and structural engineers are working based on different criteria of their own profession in building design process, and the two criteria often conflict with each other. Although structure is considered as one of the main aspects of architecture, it is not easy for architects to employ it as a positive factor that adds value to their design. On the other hand, structural engineers

always have to realize ideas of architects which may not be structurally efficient, and they usually act passively in design processes. The conflict of architecture and structural engineering resulted in low efficiency, waste and restriction in architectural creation.

Structural form design could be considered as a bi-objective problem which needs to satisfy efficiency criterion of structural engineer and at the same time the aesthetic criterion of architects. Since architects and structural engineers are thinking in very different ways, it is not easy that someone can employ knowledge of both professions in creation of structural forms. Development of computer hardware and structural simulation software in recent years raises one possibility that computer may assist architects in early stage of design by providing multiple alternatives of structural forms for them.

The interactive genetic algorithm (IGA) method combines the advantage of human in subjective evaluation and that of computer in searching, and provides an interactive method of subjective design. In an IGA process, the designer evaluates a group of design proposals generated by computer by scoring them, then the computer generates new design alternatives based on the scores using genetic algorithm (GA), and then the designer evaluates again. As the interactive process goes on, some preferred designs could be achieved effectively. (Figure.1)

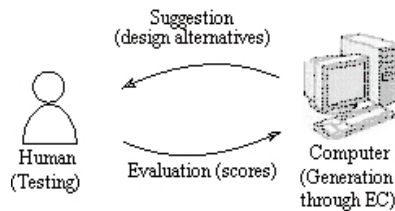


Figure 1. Mechanism of IEC method

In this research, it is expected the IGA method could provide a frame work which allow architect and computer working together on the bi-objective problem of structural form design, in which computer organizes the interactive evolutionary process and performs structural optimization, while architect influences the evolving of structural forms by providing subjective evaluation of them. The structural forms in IGA process are expected to evolve into some alternatives that satisfy both the criterion of structural optimization and that of human subjective evaluation.

2. Past studies

There are a lot of researches that apply IGA in various subjective design problems. Aoki and Takagi (1997) applied it to 3-D CG lighting design, and compared its efficiency in helping professionals and non-professionals. Experiment shows the method effectively works in assisting amateur designers. This result suggests that IGA may help architects in structural form design since they are amateur in structural engineering. Matsushita and Munemoto (2004) use IEC and CG in searching for façade glass attributes which performed ideally in day and night. The colour, reflectance, and transmittance of glass are adjusted according to the designer's subjective evaluation. Huang, Matsushita and Munemoto (2006) try to apply IGA method in Chinese apartment interior design to help the non-professional residents in performing interior design by themselves. IGA process is adjusted to and proved significant in improving searching efficiency. A recent research of Tollena (2010) employed IGA in collecting information for prioritizing the requirements for a software system, and the result outperforms GA.

On the other hand, there are a lot of researches on structural form generation. Xie and Steve (1997) use an ESO method to generate structural form by eliminating low stressed material in an evolutionary process. This method has been developed and applied in real project in recent years. Kawamura and Ohmori (2001, 2002) propose a topology optimization method of frame structures by GA. In order to produce structural topology which is stable and without needless members, the generation of structural form is based on triangle units, not members. Experiment show the method can generate various frame structure topologies and is effective in optimization. In this research, the method of Kawamura and Ohmori (2001) is employed in generation of structural form. Different from the above-mentioned IGA researches that focused on the subjective criterion, and the structural form generation researches that optimize structural form according to structural engineering criterion, the present research is a human-computer interactive process that optimizes structure forms according to two criteria, and intended to find out structure forms that are both structurally optimized and appreciated by the architect who operates the system.

3. Method

3.1. STRUCTURAL FORM GENERATION

In this research, the frame structure generation method proposed by Kawamura and Ohmori (2001) are employed to generate structural form. The basic

elements are not members, but triangular elements composed of 3 members in planar situation, or a tetrahedron frame connects 4 nodes in 3-dimensional situation. The advantage of this method is the frame structures generated are guaranteed to be structurally stable and with no needless members that are not properly connected to the main structure.

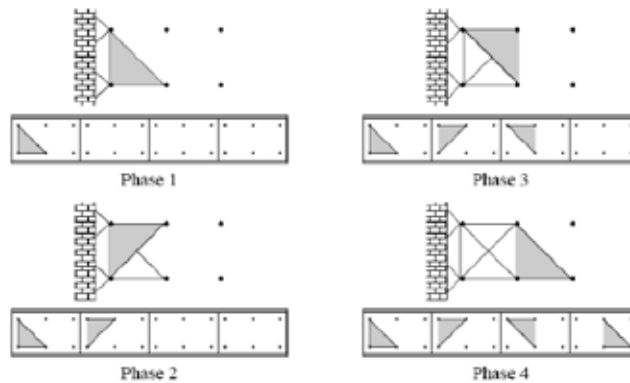


Figure 2. Truss topology consisting of triangles (Kawamura and Ohmori, 2001)

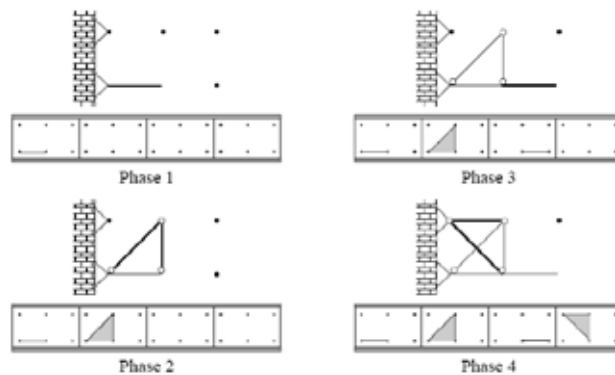


Figure 3. Hybrid topology of truss and beam members (Kawamura and Ohmori, 2001)

Figure 2 shows the generation process of a truss structure. In each phase, the triangular truss element is added according to the condition that two of its nodes are supported joints, or already connected to existing members. Figure 3 shows how a hybrid topology which consists of truss and beam members is generated. When adding a beam member, it must be connected to an existing beam member to make it stable. If only truss members are connected to it, one of the truss members will be changed into a beam member. The generation

process ended when all supported joints and loaded joints are connected by the elements.

Structural design is a complex problem, and in this research, the structural forms generated are only expected to be heuristic for the architects in conceptual design stages, and further analysis and design need be carried out by professional structural engineers to achieve the final design results. In addition, the structural analysis in this research only considers elastic analysis of a static load condition in order to focus exploration on the bi-objective optimization process. This simplification also benefits the research by reducing time for structural analysis and making the length of the interactive process acceptable for architects. Structural analysis is performed by Openses¹. An iterative process is programmed to call Openses to find out proper section radius of each member. The evaluation of structural efficiency is based on the weight of the structures.

3.2. HUMAN-COMPUTER INTERFACE

IGA system usually provides a human-computer interface which allows multiple alternatives be displayed simultaneously on computer screen for compare and evaluation. In this research, the interface is developed based on Rhinoceros 3D modelling software. Various structural forms could be displayed in 16 juxtaposed views. The models could also be viewed 3 dimensionally, and each view could be extended to the whole interface to allow detailed observation if needed. A panel for controlling the evolutionary process and input evaluation of structural form alternatives is programmed using C# language (Figure 4). Architect can select their preferred forms by checking the CheckBox.

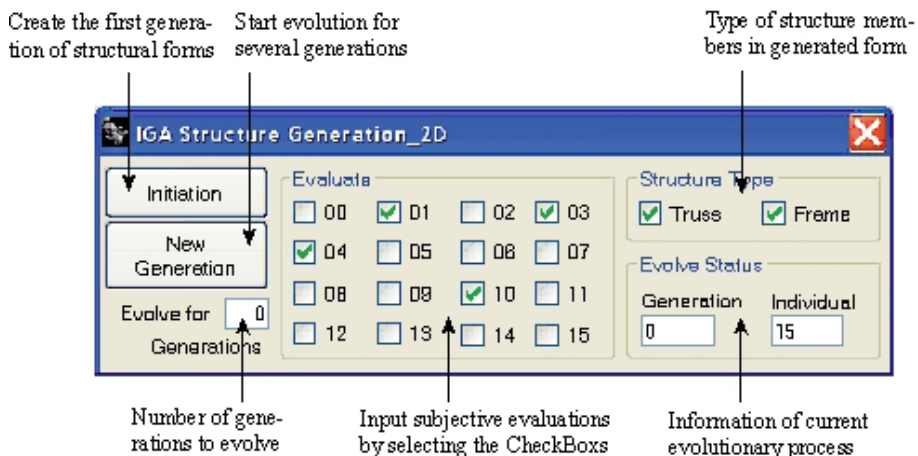


Figure 4. Panel for inputting evaluation and controlling evolution

3.3. EVOLUTIONARY PROCESS OF BI-OBJECTIVE IGA

In process of the bi-objective IGA, both the rational evaluation of structural efficiency by computer and the subjective evaluation of spatial form by architect will lead the evolution. In order to combine these two criteria, the fitness function of IGA takes the sum of both evaluations. In IGA process, human fatigue refers to the phenomenon that human users get tired when evaluating alternatives repeatedly generation after generation, and it is one of the most crucial problems for IGA application. From the research of Kawamura and Ohmori (2002) it is understood the GA optimization could last for hundreds of generations, which makes evaluating of every alternative in the process impossible. In the IGA system, the user can choose to evaluate every several generations to reduce his work.

Another problem of bi-objective optimization is that the two criteria could be independent, and even contradictory, and it will be very difficult to find an optimum solution if this happens. In a common design process, if the architect understands structural design problem very well, it will be much easier to develop a good scheme from both the view of architecture and structural engineering. In this research, the structural forms are sorted by structural evaluation before displayed in the interface. With this procedure, the architect could easily know which alternative is structurally more efficient, and the price he needs to pay for the selected form if it is not the most efficient one. In order not to lose good alternatives in IGA process, the best one is copied directly to the next generation.

4. Experiment

In this research, a structural generation problem is proposed as shown in figure 5. The 12 nodes are set with designated positions, load and support conditions. In the generation process, elements are added to connect these nodes to form a structure. Structural symmetry is employed to reduce amount of computation.

4.1. SINGLE OBJECTIVE OPTIMIZATION

In order to verify the efficiency of the IGA system in structural optimization problem and to provide a comparison for bi-objective evolutionary process, a GA process without subjective evaluation is performed. Figure 6 shows the first and final generation of the structural forms, and figure 7 shows the evolution of structural weight through the process. The white members are beam members that bear axial force and bending moment, and black members are truss members that bear only axial force. It is revealed the structure form evolves effectively, and the weight of the structures decreases significantly in

early generations.

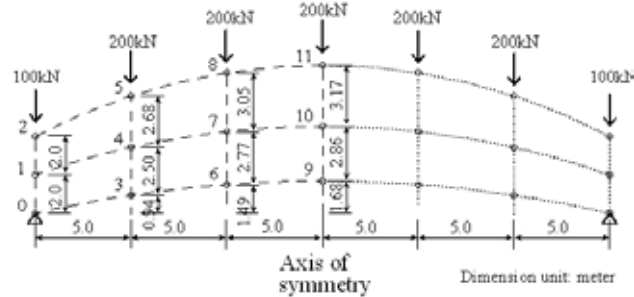


Figure 5. Designated node positions, load and support conditions

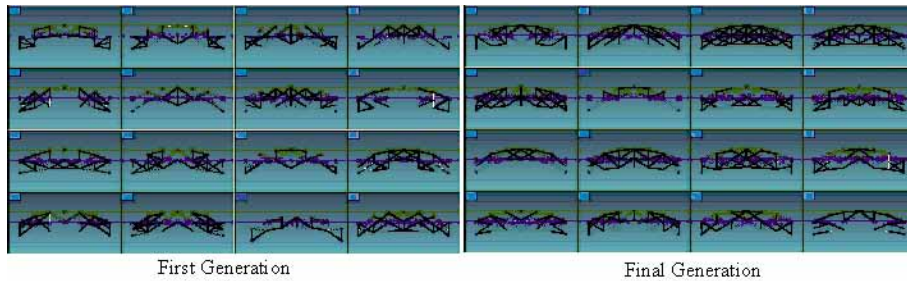


Figure 6. The process of one-objective GA

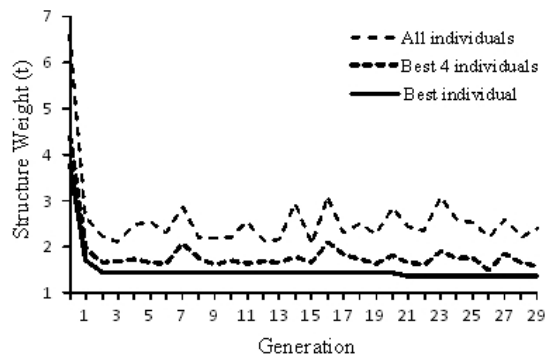


Figure 7. The process of one-objective GA

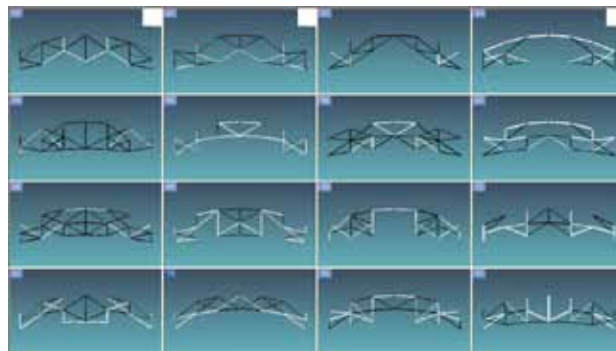
4.2. BI-OBJECTIVE STRUCTURAL FORM GENERATION

An architectural student is asked to use the system to find ideal structural form for himself. He is told the alternatives displayed are sorted by their weight, so the upper ones in the interface are structurally more efficient than the lower ones. He is also told to select several alternatives in each generation according to his own preference, and the alternatives are expected to evolve towards

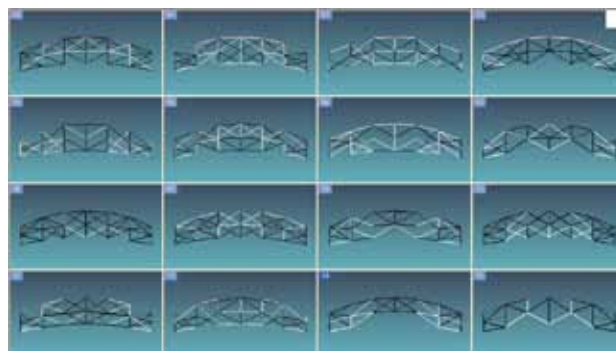
some results that are good both in structural efficiency and his own aesthetic preference.

The architectural student reports that his objective in the process is to find some structural that has a complete arch form at the top, and he wants the lower-middle part to be empty to provide more interior space. He also tries to avoid selecting alternatives in the lower part of the interface because they are not structurally efficient. The evolution process is shown in figure 8 with white squares marking the alternatives he selects, and the evolution of structural weight is shown in figure 9.

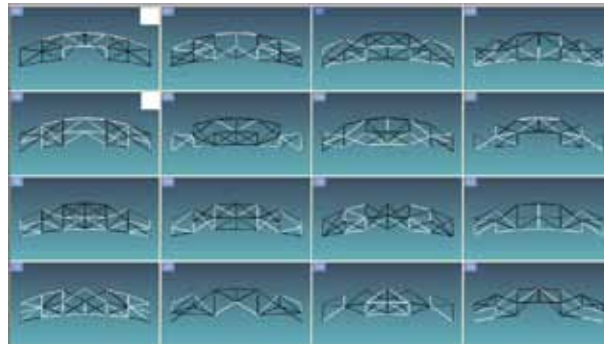
It is found that certain topologies of structural form preferred by the student are transferred through generations (figure 8). At the same time, weights of the structures decrease through the process (figure 9). But since it is a bi-objective process, the two criteria have restrictions on each other. In later generations the two criteria compete with each other. The student does not find a result that ideally satisfies his objective, and the weights of structural forms do not decrease significantly after generation 1.



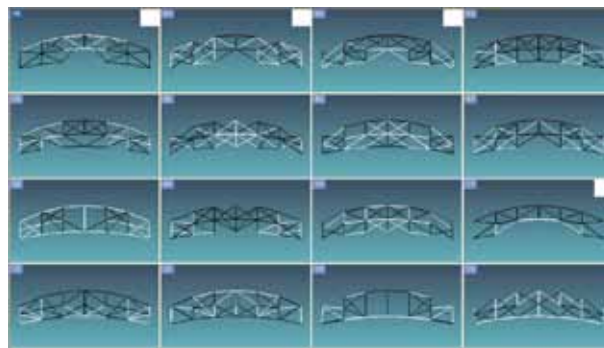
Generation 0



Generation 1



Generation 3



Generation 5

Figure 8. Evolution process of bi-objective generation

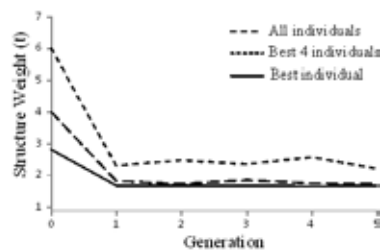


Figure 9. Evolution of structural weight of bi-objective generation

5. Conclusion

In order to help architects in the bi-objective problem of structural form design, this research tries to use IGA to combine the structural analysis performed by computers and aesthetic evaluation of architects. The method of triangular

units is adopted to generate structural form. A human-computer interface is developed to allow 3D view of the structural forms and evaluation of them. Through experiments of the bi-objective problem solving process, it is found both of the two objectives affect the optimization, and the two objectives have mutual restrictions. In later generations the two criteria compete with each other, and the achieved result is a compromise of them.

Since understanding of structural problem is important for architects in their creation, the alternatives are sorted before displayed in the interface in order to let the architects know the structural price they need to pay for a certain scheme. Because of this measure, the bi-objective IGA system is also meaningful in the aspect of architectural education. Mutual restriction of criteria is very common in bi-objective problems. It is not expected the proposed IGA system can find a solution for such restrictions. In fact, the system can be helpful for people in understanding such problem, and thus be helpful for people in solving it.

Endnotes

1. The Open System for Earthquake Engineering Simulation (OpenSees) is a software framework for simulating the seismic response of structural and geotechnical systems. It has been developed at the Pacific Earthquake Engineering Research Center.

Acknowledgements

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DAYLIGHT AND ENERGY IN THE EARLY PHASE OF ARCHITECTURAL DESIGN PROCESS

A design assistance method using designer's intents

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Abstract. The integration of daylighting from the beginning of the design process can help designers to create buildings that respect their environment benefit from the solar gain thus giving an answer to illumination and energy needs (Bodart et al, 2002). This paper proposes a declarative assistance method/tool designed for the early design phase. This method assists the designer in integrating the daylight and its energetic impact from the beginning of the architectural design process by means of intents. The intents are related to the daylight, energy and spatial configuration aspects of the architectural project. The method translates the designer's intents into potential solutions. They are the first formal representation of the architect's intents that could be customized and altered during the next architectural design phases.

Keywords. Daylight; energy; early design phase; design support; intents

1. Introduction

The environmental awareness urges the designer to integrate the daylight and its energetic impact into the early phases of the architectural design process. "Decisions taken rapidly in the early stages of design can have a large impact on the performance of the finished building." (Gratia et al, 2001). Several design assistance methods propose to help the designer to realize a better

integration of the daylight and the energetic impact in different phases of the design process. They mostly involve in-depth knowledge without a real integration method and are designed to evaluate the performance of architectural shapes under criteria in relation with daylight and energetic features. This type of method/tool is characterized by the lack of elements that can support the design process during its first steps. The reason is that these engineer's methods/tools are developed to answer needs that are different from the architect's ones. A new generation of prototypical methods propose to assist the architect by integrating architectural knowledge in early design phases. Among these methods, the declarative modelling one uses the intents as a main data to establish a real dialogue between the method and the designer. It uses the designer's intents to propose potential solutions.

Our research subscribes to this way and defines a method that must:

- Integrate the daylight and its energetic impact
- Be adapted to the starting phase of the architectural design process
- Allow a real dialogue with the designer

The first part of this paper presents two types of methods integrating the daylight and the energetic aspects. We present the process, the different actor's (person and system) tasks, the manipulated data types and if they answer to our expectations. In the second part, we present the process and the different phases of our assistance method integrating the daylight and its energetic impact by the use of the designer intents.

2. Design assistance methods

Different design methods are developed to assist the designer on the different tasks during the architectural design process. These methods focus on particular domains of the architectural project as the daylight, the energy or acoustics. They take part in the architectural design process by different ways and at different phases. The evaluation of an array of methods allows the identification of two major method classes, the decision support method and the design assistance method.

2.1. DECISION SUPPORT METHODS

This class of methods is designed for engineers and used to realize quantitative evaluations of architectural project features like the energetic, acoustic or daylighting behaviour. They participate during the last phases of the architectural design process where the evaluations results make sense to validate some designer choices or strategies (Figure1). Among these methods the models ones (the modular climate chamber¹, the Heliodon², the Scanning Sky Simu-

lator³), the simplified calculation methods (LUMcalcul) and the simulation software (Dialux[®], Ecotact[®], ArchiWizard[®]).

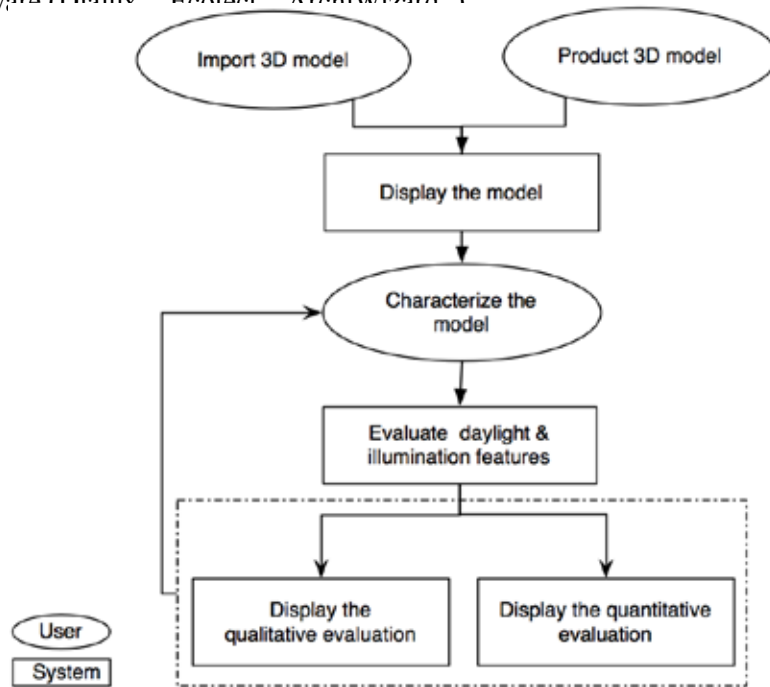


Figure 1. The process of standard support decision method

Dialux[®] import 3D models of architectural projects from standard CAD systems to test different illumination strategies and evaluate their daylighting or artificial lighting behaviour. These models must be formalized and characterized to make the simulation possible. The user must define the project features, i.e. the orientation, the surfaces characteristics, the light sources. The simulation results concern the quantitative evaluation as the photometrical values (daylight Factor, Luminance, etc.) and the qualitative ones (photorealistic representation of the generated daylighting effects).

The decision support methods can hardly be used during the early phases of the architectural design process because the designer is not able to define the different features characterizing the project. Indeed, Lawson (Lawson, 2006) defines the “moving activity” characterizing the starting phases of the design process where the project is still on the drawing board. The “moving activity” integrates the designer intents generation and transformation to propose potential solutions. But, these support decision methods are not able to support this design activity.

2.2. ASSISTANCE DESIGN METHODS

Different research groups in architectural domain propose a new generation of assistance design methods linking the popular three-dimensional CAD modeller (Rhino[®], Sketchup[®]) with advanced daylight simulation tool (Radiance, Daysim). It makes possible the evaluation and the validation of a large number of designs variant at the early stages of the design process. They produce a quick feedback integrated on the project development. The DIVA (Lagios et al, 2010) workflow integrates on Rhino[®] single and multiple evaluation of the daylight behaviour of schematic design configuration. Light-Solve (Andersen et al, 2008) is a plugin for Sketchup[®] used to analyse and to visualise the daylighting effects from different viewpoints of the project and under various sky conditions.

Another type of methods integrates some architectural knowledge to assist the design process. They use the declarative modelling method using designer's intents to generate potential solutions. The intents represent the architect's choices or the design constraints concerning a particular aspect of the project creation. They are described using architectural terms (Lassance, 1999). This method is used in different architectural assistance method designed to create real dialogue between the designer and the method. Three actors (system, person) are participating in the declarative modelling process: the "user", the "interface" and the "system". The declarative process is organized in three phases; the "describing", the "generating" and "assessing" phases (Figure2).

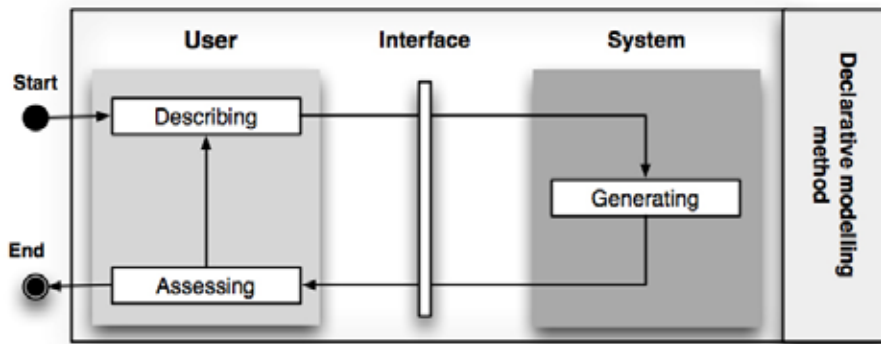


Figure 2. The declarative modelling process

On the "describing" phase, the "user" describes his intents using an architectural language in relation with a particular aspect of the architectural project, like the daylight atmospheres for instance. During the generation phase, the "system" translates the designer's intents into geometrical constraints to generate solutions. The "user" participates also in the "assessing" phase during

which he evaluates the generated results. Following that, he can select solutions that are corresponding to his intents.

This method is used to assist different tasks of the architectural design project. With the WordsEye (www.wordseye.com) project the user gives the description of a desired 3D model, expressed in a natural language. A very important database is used to translate the sentences in a set of constraints and generate 3D models (Figure 3).



Figure 3. WordsEye modelling process, (A) describe the scene, (B) show the 3D scene, (C) show the 3D scene components.

Fauche (2000) proposes a declarative method integrating the designer intents related to sunlight, visibility and urban regulation. It uses an architectural knowledge base that translates the described intents into constraints to make the generation of potential solutions possible. The method proposes potential geometrical configuration of sunscreens or building shape generating the described intents (Figure 4 and 5).

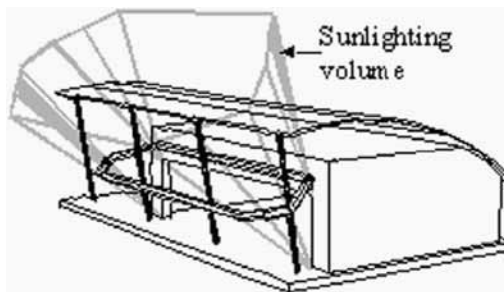


Figure 4. Proposed solution to the daylight intent "The front of the project must be sunlit in the middle of the day in winter".

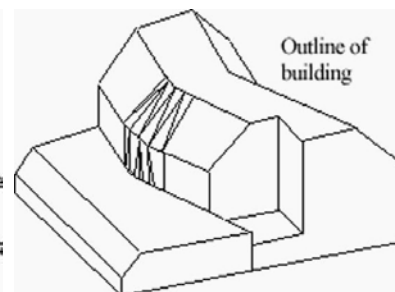


Figure 5. Proposed solution to the urban and visibility intent "The building must be included in the maximal volume of the site".

Leso-Dial (Paule and Scartezzini, 1997) is a declarative tool allowing the designer to describe a spatial configuration using an architectural language, to evaluate the daylighting results. An expert diagnosis allows architect to point out the possible weak points of their design (Figure 6).

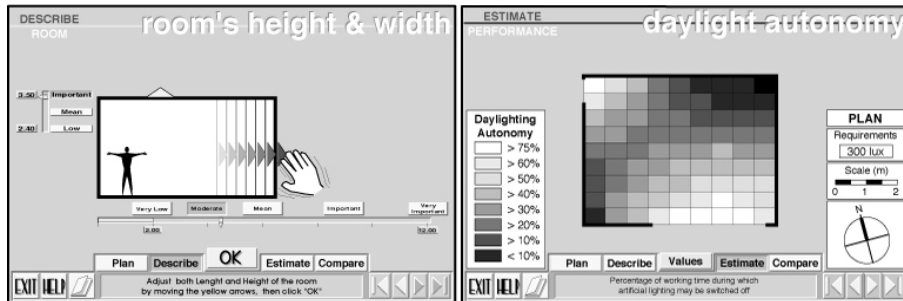


Figure 6. Examples of graphic input and output on Leso-Dial

3. Proposed design support method integrating daylight and its energetic impact

We propose a declarative design support method using the architect's intents to generate potential solutions. The intents are the representation of the daylighting effects or atmospheres that the architect would like to create. The main feature of this method, that makes it different from the other assistance methods, is the integration of architectural knowledge linked to the daylight, spatial and energetic domain of the project. This knowledge will be used as a reference to translate the designer intents into potential solutions. The solutions are a formal representation of the architect's intents. The method allows the evaluation of the energetic behaviour of the proposed solutions that constitutes another selection criterion.

3.1. THE METHOD PROCESS

In our declarative modelling method six actors are participating in the process; the "designer", the "interface" and four different "systems". Two external "systems" participate in the method process, which are the "simulation system" and the "C.A.Drafting system". Every actor realizes different tasks, which are successively organized to constitute the method process. First, the "interface" presents different intents imported from the "intents database". Then, the "designer" chooses intents that the "generating system" will integrate to generate potential solutions. After that, the "Simulation system" eval-

uates the qualitative and the quantitative features and the energetic impact of the proposed solutions. The “interface” presents the evaluation results. The “designer” assesses the results and selects the solution(s) that is (are) corresponding to its intents (Figure 7).

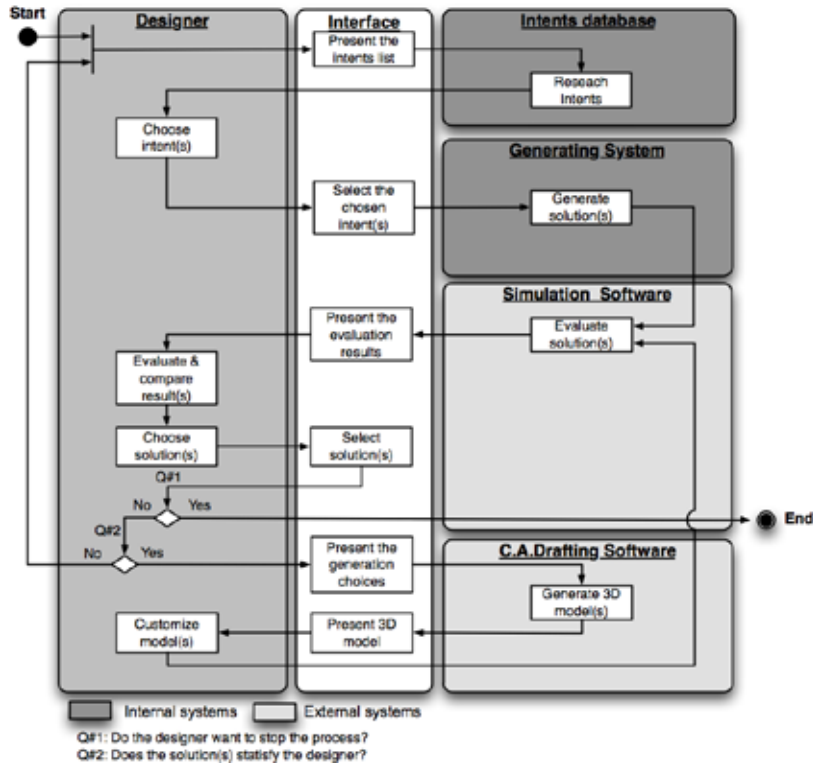


Figure 7. The proposed method process

Finally, the designer can choose to stop or to continue the process. If he chooses to continue, two cases are proposed:

- If he is satisfied with the generation results, he can generate 3D model(s) that will be further customized and evaluated.
- If he is not satisfied with the generation results, the “designer” can restart the whole process and select other intents

3.2. THE INPUT DATA TYPE

The main data used in the proposed method is the designer’s intents. Faucher (2000) defines them as “a conceptual expression of constraints having an influence on the project”. They are described using an architectural language

and characterized using the concept of indices introduced by Mudri (1996) who proposes an evaluation method of the daylight and energetic behaviour of project sketches. The indices could have a symbolic value that represents an aesthetic quality or a numerical value as dimension, reflexion factor (Marin, 2008). We use these indices to structure an intents database that participates in the system process (Figure 8).

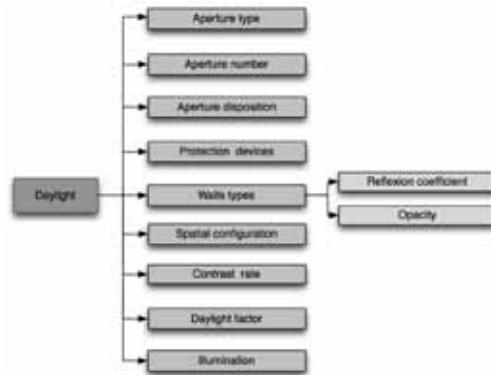


Figure 8. The list of indices characterizing the daylight intents

The intents are graphically represented by expressive icons that create a real dialogue between the designer and the system. (Figure 9)



Figure 9. Graphical representation of the daylight intent "Sunspots" (www.audience.cerma.archi.fr)

3.3. THE OUTPUT DATA TYPE

The proposed method considers the architectural project as a set of spatial units because of its complexity. A spatial unit is defined as the smaller part

of the project. So, the generated solutions will be presented as a spatial unit creating a particular daylight effect or atmosphere. These cases include all the features of the architectural project. The objective of such a method consists in assisting the architect to take into account daylight effects and its energetic impact through the manipulation and the transformation of these formal cases (Figure 10).

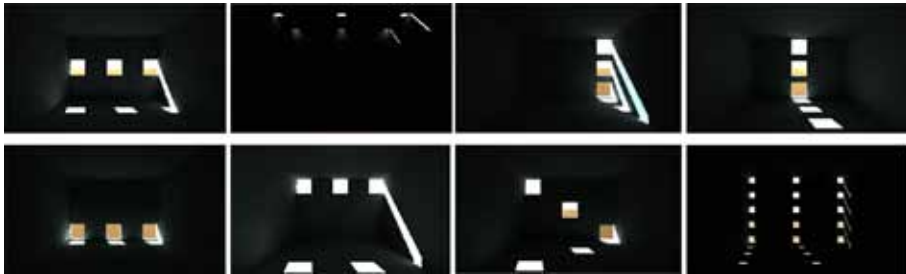


Figure 10. Examples of generated solutions

The evaluation of the energetic behaviour of the proposed solutions helps the designer to integrate this aspect in his architectural design process. The different aspects influencing the energetic impact will be evaluated by the use of indices. These indices were identified and selected because they are influencing the energetic behaviour of the architectural project.

4. Conclusion

This paper presents the first part of our research work. It proposes a declarative method to assist the designer during the early phases of the architectural design process. The only data used is the designer's intents related to the daylight atmosphere. The designer intents are characterized through the use of the concept of indices. The method generates potential solutions that are the formal representation of the designer intent's. An evaluation system is integrated to help the architect to make possible the interaction between the design choices and their energetic impact. The different input and output data are graphically represented to create a dialogue between the method and the user.

During the next step of our research, we will try to detail the different parts of the proposed method as the structure of the intents database and the generating process to develop a prototype. The objective is to evaluate the participation of this method in the architectural design process and its ability to help the architect to integrate the daylight and its energetic impact on the design process.

Endnotes

1. The Modular Climate Chamber consists of light elements and insulating modules of 120 cm² which allow the construction of different simple or multiple volumes, interconnected or not, for diverse studies regarding the indoor environment. The chamber is equipped with a double-flux air conditioning unit of 1000 m³/h that allows heating, cooling and air humidification.
2. The Heliodon is used to examine how direct sunlight interacts with an architect's building design.
3. The scanning Sky Simulator developed at LESO-PB, used as a basis for several other sky simulators, allows accurate reproduction of the luminance distributions of every type of sky. It can be used for diffuse light measurements within building scale models for any time of a year and any location and is thus a precious tool for the testing of innovative architectural solutions and daylighting systems.

Acknowledgements

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AUTHOR INDEX

- Al-Kazzaz, D. A., 545
Anders, P., 209
Anderson, J., 91
Barker, T., 335
Bartram, L., 133
Bernal, M., 19
Bridges, A., 545
Brown, A., 505
Bur, D., 761
Burry, M., 29
Burry, J., 29, 525
Celani, G., 389, 643
Chae, H. H., 375
Chalup, S. K., 493
Champion, E. M., 241
Chang, T.-W., 663
Coorey, B. P., 39
Cromarty, J., 219
Datta, S., 175
Davis, D., 29, 155
Dekker, A., 241
Donn, M., 599
Dorta, T., 271, 291
Drogemuller, R., 525, 731, 301
Duarte, J. M. P., 389, 643
Enoki, M., 483
Fernando, R., 731
Fischer, T., 623
Frazer, J., 301, 525
Fraser, M., 599
Fukuda, T., 321
Gallas, M.-A., 761
Garagnani, S., 717
Gardner, N., 335
Garner, S., 101
Gero, J. S., 399, 453, 633
Goodwin, R., 219, 229
Grace, K. S., 453
Gu, N., 1, 251, 697
Haeusler, M. H., 335
Halin, G., 761
Ham, J. J., 589
Hamadah, Q., 419
Hao, H., 281
Hanada, Y., 483
Hanafin, S., 175
Hedley, M., 229
Herr, C. M., 1, 569
Hovestadt, L., 443
Huang, W., 751
Indraprastha, A., 473
Iordanova, I., 409
Jalalian, A., 455
Jowers, I., 101
Jupp, J. R., 39
Kalay, Y., 271
Kelly, N., 633
Khoo, C. K., 143
Kidosaki, N., 483
Kim, J. J., 61
Kim, M. J., 375
Kitagawa, K., 321
Ko, K., 71
Kozlova, K., 133
Lai, I.-C., 663
Lee, J., 199
Lee, J. H. 81, 375
Lee, S., 443
Lesage, A., 271, 291
Li, B., 123
Li, R., 123
Lin, C.-J., 535
Liotta, S.-J., 71
Lo, C.-H., 663
Lonsing, W., 209
Loveridge, R., 165

Lowe, R. , 219, 229	Shinozaki, M., 473
Maher, M. L., 687	Steel, J., 731
Matsumoto, Y., 483	Takenaka, T., 49
Matthews, L., 463	Tan, B-K., 189, 311
McKay, A., 101	Tang, M., 91
Merrick, K., 697	Jia, T.-L., 281
Mueller, V., 409	Tomitsch, M., 335
Murty, P., 687	Toth, B., 525
Muslimin, R., 9	Ueno, M., 355
Naka, R., 483	Vaughan, J., 493
Nakano, A., 355	Vaz, C. V., 643
Nakapan, W., 251	Wakita, A., 355
Niazi, M., 697	Walsh, A-M. 579
Nguyen, T. L. T., 189	Wang, T., 751
Okabe, A., 49	Wang, X., 375
Okada, Y., 677	Wang, Y. P., 653
Ostwald, M. J., 493, 555	Watanabe, S., 261
Park, H-J., 61	Webb, N., 505
Parton, S., 365	Woodbury, R. F., 133
Paulini, M., 687	Wu, Y., 81
Pedreira, N., 101	Xu, W., 751
Pérez, E., 271, 429	Yabuki, N., 321
Perin, G., 463	Yamaguchi, S., 483
Pourmohamadi, M., 399	Yeom, J-H., 311
Prats, M., 101	Yuan, X., 81
Qu, Y., 741	Zhang, W., 653
Reffat, R. M., 609	
Richards, D., 515	
Rolfe, B., 175	
Roudavski, S., 1, 365, 579	
Salama, T. A., 345	
Salim, F., 113, 143, 155 525	
Santo, Y., 301	
Saunders, R., 399, 453	
Schnabel, M. A., 1, 589, 741	
Shafi, K., 697	
Sharaidin, M. K., 113	
Sheikholeslami, R. M., 133	

