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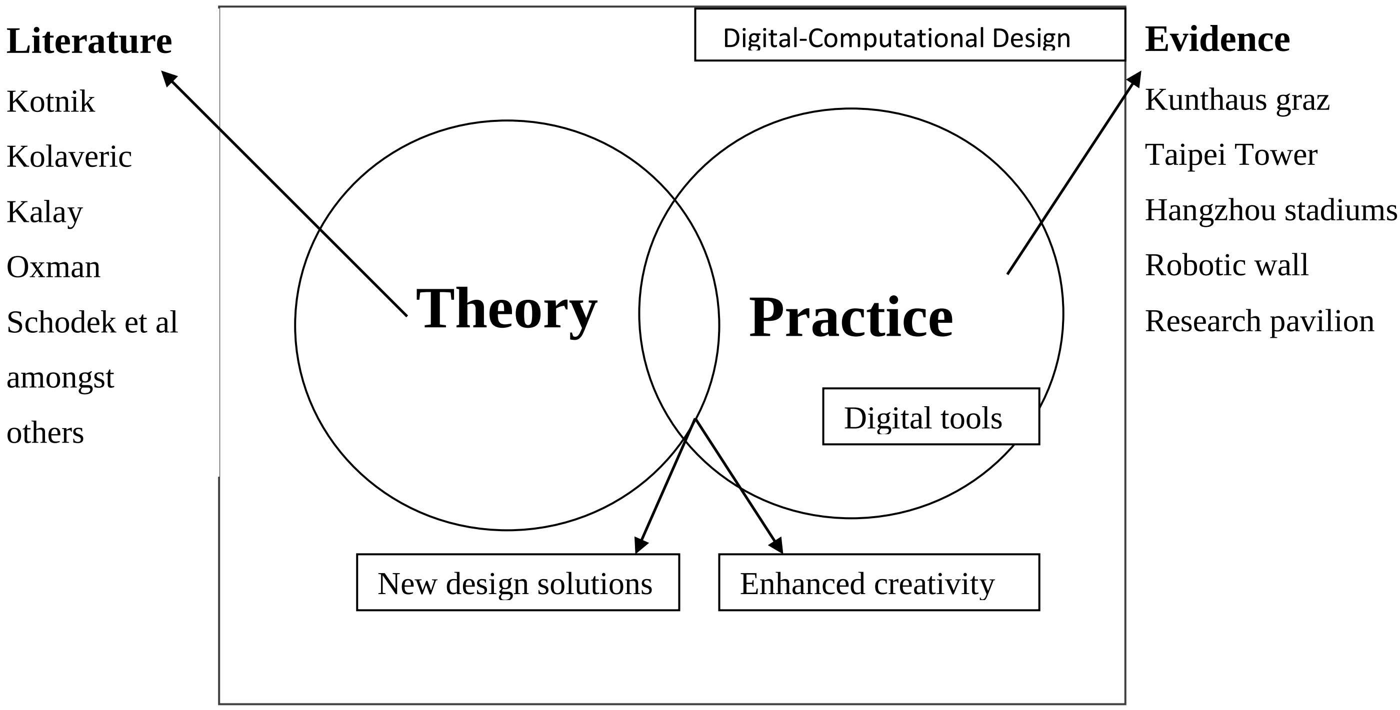
Literature
Kotnik
Kolaveric
Kalay
Oxman
Schodek et al
amongst
others
Digital-Computational Design
Theory
Practice
Digital tools
New design solutions
Enhanced creativity
Evidence
Kunthaus graz
Taipei Tower
Hangzhou stadiums
Robotic wall
Research pavilion

The University of Salford

School of the Built Environment

THE IMPACT OF DIGITAL-COMPUTATIONAL DESIGN ON THE ARCHITECTURAL DESIGN PROCESS

by

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supervised by

Dr Riccardo Balbo

A thesis
presented to the University of Salford
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in
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Abstract

This research focuses on the evolving nature and concepts of digital- computational designs and attempts to elucidate the impacts on the architectural design process. The motivation for this thesis is based on the recent interest in various Architectural conferences and publications on the effects of the process change caused by digital means. The study is centred on the assumption that computational methods have enhanced creativity and proffered design solutions that could not be achieved by conventional means. The answers to this assumptions and questions have been sought through a thorough exploration of the diverse concepts and tools and processes that enable design computation. It then proceeds to investigate design projects executed by contemporary architects that engage in the use of computation. The findings from the inquiry ascertains the hypothesis and explicates the benefits inherent in the projects investigated. It concludes by highlighting the need to sensitize and raise the awareness of professional and students on the benefits and potentials of design enabled by computation.

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Finally to my family, especially my mum for teaching me that there is dignity in labour. Love you so much. You are my 'S-hero '.

Declaration

This work is being submitted in partial fulfilment of the requirements for the degree of Masters in Digital Architectural Design and has not been previously accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

Signed ________________________________ Hauwa Olabisi Yusuf

Date ________________________________

Chapter **1**

1.0 Introduction

Creative ideas of prolific designers and inventors such as Da Vinci from the renaissance age, were inhibited by the lack of materials required to convert their thoughts into reality. The constant evolution of the human society as identified by Fresco, has resulted in both social and technological changes (Gazeki, 2006). The most remarkable technological transformation is the invention of electronic computers in the mid 20th century. The automation of repetitive arithmetic and logical tasks and the speed at which they are executed is undoubtedly advantageous because, with the advent of computers, came a change in the way different professionals communicate, collaborate and perceive tasks. The Architectural field is not excluded as it has been greatly reshaped. Design teams progressively rely on computer technology, as an aid to virtually represent or in most cases clarify their ideas and visions. It is an apparent reality that with the change in design media, came a reorientation of the design process as every activity or thing is influenced by the environment within which it exists.

With this change in design processes comes a critical scrutiny of the Architect's role, mental abilities amongst other concerns. There are various perceptions of the influence of computation. A school of thought considers the invasion of computers into practice as sullying, another perceives design computation as mere evolution of traditional processes, while the third and most radical view is that of Intellectual revolution.

However, one development common to all these schools of thought is the question of how digital technology influences individual practices (Smith,2005). This statement forms the basis for this research.

1.1 Aim

This research aims at investigating and evaluating the impact of the emerging practice of ‘non-standard’ architecture on existing architectural processes.

- The research hypothesis states that computational approaches are problem solving and have profoundly enhanced creativity in traditional architectural processes.

1.2 Research Objectives

The research aim will be achieved by

- Examining existing(non-computational) architectural design processes.
- Reviewing extant literature to define digital-computational design.
- Reviewing the various approaches in digital-computational design.

- Investigating recent professional projects in the field of computational-digital architectures.
- Concluding by identifying the benefits and/or shortcomings of using a computational approach to designs.

1.3 Methodology

The research will be conducted through a critical and qualitative analysis of case studies which is the main means of through which the data was collected. Contemporary architectural firms, and their projects that have been successfully executed, will be studied. The first case would analyse a project initiated by 'traditional' means of design, while the subsequent cases present analyses of projects in which design computation was utilised. The intention of this research is to compare and contrast findings in order to identify similarities and or differences.

1.4 Scope

This thesis is limited to the various solutions that computational methodologies have offered during design phases with particular focus on the conceptualization stage and the tools that enable the identification solutions to perceived design problems.

1.5 Justification

Due to the evolving nature of Digital-computational Architecture, its potentials have not been fully appreciated nor widely accepted. In the early stages of digital revolution, design computation was employed as an aid for the commercial processes in praxis such as Drafting, 3D renders and visualisation.

As Burry identifies in his most recent publication on *Scripting Cultures*, "for decades architectural software has striven to emulate the analogue working practice that architects developed over the past two centuries" (Burry,2011). This indicates that modern technology attempted to emulate what is already in existence.

In its inception, computation methodology served to test the practicability of the architect’s designs and how such designs could be physically realised. Thus, making computational processes an aid to the traditional architectural design process. However, it was found that where computational processes were adopted, it influenced the initial designs of the architect and instructed minor changes (Leach, 2009).

The assistive premise of computational methodology is most aptly captured in the now commonly used phrase ‘Computer-aided architectural design.’ Since its introduction into the traditional architectural design process about forty years ago, the role that computer technology plays in design has continued to expand in relevance and use. In recent times, evolving schools of thought on the design process broach the possibility of the use of computers in generating a totally computer-directed design process. (Mahalingam, 2003).

On the practical side, competence in computer technology now plays a more central role in assisting budding architects to get jobs with already established architectural practices, further highlighting the increased premium placed on the knowledge and application of computer software to design by the architectural industry (Tomassian & Marx, 2003). This may largely be attributed to the fact that the way designers exchange and present ideas has changed due to the influence of computation. This change and its effects on design culture have in the recent past been the headline of most conferences and journals of architecture.

John Lobell in his article titled Cultural Concerns in Computational Architecture, made reference to traditional modernist G. Holmes Perkins. Perkins, he stated, "had always said that architecture must have an ethical, social and aesthetic component, otherwise it is just fashion. This attitude was lacking at the Non-Standard Praxis conference and among many of today's computational architect" (Lobell, 2004).

As architectural offices are becoming de-centralized in this era of technological and historical change, it is necessary to evaluate the impact of this emerging field on traditional design processes and ascertain if it is a new and unique mode of design or just the conventional design realised through new means.

1.6 Structure of the Report

The subsequent chapter identifies the nature of this theses and the mode of data collection. It also examines the strategies and techniques employed in the analyses of the data collected. Chapter 3 comprises of information retrieved from the review of extant literature. It comprises of an overview of design processes, a simultaneous discussion on design computation and creativity, digital design media and prototyping methods. It ends with a detailed exploration of design processes identified by a prominent architectural researcher. Documented in Chapter 4, is the analysis of the cases studied using the design processes discussed in the previous chapter as a tool for analysis. The last Chapters present the discussions and conclusions respectively. A detailed comparative analysis is presented with the aim of identifying similar or disparate patterns, design solutions proffered as a result of computational design, the level of creativity amongst others.

Chapter **2**

Research Methodology

2.0 **Introduction**

This chapter proceeds by describing the research and the various strategies that will be utilised. It also discusses the method of data collection and proposes the sources from which they will be obtained. Alternative methods of data collection are examined and rationale for the choice of the selected approach explained. The chapter is concluded with a description of the proposed mode of documentation for the data retrieved during the course of this study.

2.1 **Research Strategy and techniques**

The study is exploratory "as it seeks to explore what is happening and ask questions about it"(Gray, 2004). It is qualitative not quantitative, thus an observational and analytical approach has to be employed. This research approach will "employ some combination of inductive and deductive analyses" (Schwandt, 2001).

The deductive approach will be applied at early stages of the research "as the literature review will help provide a source for the focus of the research" (Gray, 2004). The Review of literature will involve, apart from the use of books, the consultation of journals, Conference papers, grey literature(blogs, websites) as they offer insight to recent research in the field of Computational Architectural design. The latter stages will be inductive, being that it is not the aim here to counter or re-establish any former theories on the subject matter but to gather secondary data in an attempt to establish similarities and incongruity in current processes and construct meanings from the data gathered (Gray,2004) .

After critical review of literature, the preferred strategy for the research as it seeks to investigate impact of 'non-standard' praxis on the design process is the use of Case studies. In some situations as stated by Yin (1994) "a specific strategy has a distinct advantage. For the case study, this is when a "how" or "why" question is being asked about a contemporary set of events over which the investigator has little or no control"(Yin, 1994).

Case study is a research approach that utilizes multiple methods, collects data from multiple levels or multiple organizations. It also encourages the investigation of organizational issues within the context in which they exist (Cameron& Price, 2009).

There is obviously far greater opportunity to delve into things in more detail and make discoveries that are possibly non-evident through survey, by providing an in-depth account of events, relationships, experiences or processes occurring in a particular instance. (Denscombe,2001).

According to Gray (2004),"the reliability of qualitative research can be strengthened by using multiple cases or supporting assertions using numerous examples". A combination of three sources of evidence will be examined. These sources include but are not limited to the following: documentation, archives and interviews. Consequently, it is noted that none of the specific sources have any significant advantage over the other; on the contrary, they are mutually supportive in order to gather robust evidence for research. Similarly, Saunders et al (2009) suggests; exploratory studies can be conducted by, a search of literature, and documents provided by experts in the contemporary design field.

Other methods of collecting evidence such as direct or participant observations were considered but excluded from this study, due to weaknesses indentified by Yin(1994). They include, cost, time consumption, potential bias due to investigator's manipulation of events amongst others.

Due to the fact that "the scale and stages of application of Computational Design in the industry often depends on the size of the practise" (Derix, 2009) at least three case studies of diverse organizations will be conducted so as to maintain the objectivity of the research. The approaches , limitations and strengths of design computation in actual practice within the practices will be examined. Another rationale for the choice of the cases is, based on Kotnik's levels of computability. The selected cases will address the representational, algorithmic and parametric levels respectively.

The first case study will investigate the Computational Design and Research group of AEDAS. The group specializes in investigating and creating in-house design simulations that aid in generating, visualizing and evaluating spatial characteristics of the built environment. "The group has an open framework which serves to explore the nature of computation as a design search instrument"(AEDAS,2012).The case study would be conducted through analysis of the design processes involved in one of the projects executed by the group.

The second case will investigate the practice of Gramazio & Kohler Architects, with focus on the process involved in the design of the 'Robotic wall' of the Vineyard Gantenbein which is situated in Fläsch, Switzerland.

The third case will examine the design process for The Hangzhou Tennis Center, executed by a architectural firm called NBBJ & a structural firm called CCDI, "where parametric workflow systems were invented to link together disparate design and documentation environments for a more seamless international collaboration" (Miller,2011).

The composition of the report will be simultaneous with the analysis stage. It will involve the documentation of methodological sections and references. Contents of notes retrieved will be analysed to reduce textual material not relevant to this research.

2.2 Practical Implementation

This section explores the various techniques of data analysis and specifies the technique intended for the analysis of the findings from the case studies.

2.2.1 Approach to Analysis

Data analysis consists of examining, categorizing, tabulating, or otherwise recombining the evidence to address the initial propositions of a study (Yin, 1994). The analytic strategy proposed for this study is, relying on theoretical propositions (Yin, 1994). The theoretical propositions of Kotnik as stated in the previous paragraph informed the choice of the case studies.

The technique of analysis proposed is the Program-logic model which is a combination of pattern matching and time-series analysis. The outcomes or effects of computational design over time will be traced in each case, and "if patterns coincide, the results can help strengthen the internal validity of the research" (Yin,1994).

Gray (2004) admonishes that, "the qualitative analysis is (should) be a rigorous and logical process through which data are given meaning". In this light, the content of the collected data will be screened for irrelevant material after which the merits or de-merits as the case may be explicated.

In order to make a significant contribution to the field of computational design, the case study report for this study will take a written and pictorial form. This will also help to sensitize and communicate essential facts about this phenomenon to various groups of non-specialists.

The structure of the report will be such that, documentation of each case-study will be done and a section at the end will be dedicated to cross case analysis, discussions and conclusions.

Chapter **3**

Literature Review

3.0 **Introduction**

This chapter begins with an overview of architectural design processes as identified by a selected number of design scholars. Definitions of design and the processes provided with particular attention to the meaning of digital-computational designs. Subsequent to this enquiry is an exploration on creativity in relation to design computation. Various views on creativity and the effect of computation on human creativity are discussed. The successive section explores the concepts , tools and processes that make design computation feasible. Classifications based on conceptual contents and approaches, the various medium through which digital-computational designs are achieved are succinctly described. The chapter is concluded with a detailed account of identified processes of digital design and an attempt is made to juxtapose the processes with tools employed at each stage.

3.1 **Overview of Architectural Design Processes**

Design is a generic and continuous activity that often deals with precise and vague ideas. Architecture being one of the most central fields in the design spectrum is one of the most publicised. According to Herbert, the architectural design process, "is a synthesis of artistic and scientific creativity and invention, resulting in architectural potential for the adaptation of the environment to defined human purposes" (Herbert,1965). The design continuum is a 'BASIC', linear process that flows from uncertainty to clarity (Frazer, 1972). It customarily begins as identified by Perkins, with the Architect's analysis, understanding and response to base data and intentions which are subsequently synthesised to form the core concept of the design (AIA,2008). Design emerges through increased comprehension of a design problem and its limitations (Kilan,2006).

The design process identified from Archer's publication in 1968 , consists of four interrelated phases namely: Problem analysis, Solution synthesis, Evaluation and Communication (Kalay,2004).

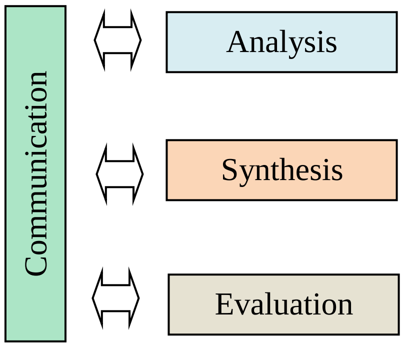


Fig1:The major components of the architectural design process (Kalay,2004)

Correspondingly, Lawson identifies the design process as a negotiation between problem and solution through the activities of analysis, synthesis and evaluation(Lawson,2006).

Breakthroughs in designs require considerable technical competence, visual imagination and design ability communicated through drawings. Drawings, apart from being artistic end products serve as tools through which architects convey their designs (Treib,2008). However, "the drawing offers a reasonably accurate and reliable model of appearance but not necessarily of performance" (Lawson,2006). During Modernism, drawing styles experienced the most notable change in architectural history. The characteristics of that era such as simplicity and the prevalent use of industrially manufactured building components have become a 'law' most designers live by, thus limiting conceptualization in the early stages of design and reducing the architect's influence in the design and production of building components. This resulted in the prevalent use of orthogonal forms in design due to the convenience of production and the total separation of designers from the 'act of making'. Industrialisation began to control the design process as designers were sometimes forced to redesign if parts needed to construct the proposed concepts were not readily available.

Then came digital media, offering designers the opportunity to envisage the performance of a building during the process of design and the means of realising geometric forms once envisioned by expressionists about a century ago(Szalapaj,2005). This marked the start of a new architectural vocabulary referred to as Bespoke or Non-standard praxis .

To support the hypothesis of this research, and evaluate whether the use of computation is avant-garde it is necessary to provide definitions for the term Digital-computational design as it is used in this context and recent practice.

"Computational design involves the employment of computational methods to design problems, whether related to presentation, analysis or aesthetic expressions" (Generatorx, 2012).

Digital- Computational architecture as defined by Liu, is "any architecture that strategically utilizes any computing digital media in the process of its architectural design-from the design concept; through early design stage, design development, detail design, and construction planning; until the actual construction". He added that this definition completely emancipates the traditional, familiar architecture as almost all practices in the world employ at least one form of computation or the other (Liu,2002).

Similarly, Kolaveric (2003) stated that "Computational, digital architectures are defined by computationally-based processes of form origination and transformations, i.e. the processes of digital morphogenesis, where the plural (architectures) emphasizes multiplicities inherent in the logics of the underlying computational concepts, such as topological geometries, isomorphic polysurfaces (blobs), motion kinematics and dynamics, keyshape animation (metamorphosis), parametric design, genetic algorithms (evolutionary architectures), performance, etc". (Kolaveric, 2003).

Computation however does not require digitization as the human thinking process can be analyzed, graphically represented and evaluated without using computers. (Terzidiz, 2003). The tedious task of computation in the pre-digital era was reliant on printed mathematical tables, differential geometry and related general theories of curved surfaces. "The tools employed in determining geometric relationships were primarily the compass and the straightedge"(Kalay,2004). This is evident in the fact that the history of Computational Design has been traced back to late 19th century Catalan Architect Antoni Gaudí. He conceived his ideas in three dimensions by modeling catenary curves by suspending linked chains. However, what distinguishes designers of the pre- digital age from contemporary designers is the detailed knowledge of the fabrication and construction processes(Szalapaj,2005).

"Since the early days of "visionary" computational architectural projects from Gregg Lynn & NOX among others, appeared the debate about blob versus box, the notion of form esthetic and the effects of such architecture"(Agkathidis,2011). The marked increase in the number or paper and web-based publications on the subject matter in the last five years suggests that digital design now represents a central topic for discussion in the field of architectural design globally. (Oxman,2006).

Form finding processes in the past were more casual, as designers could not represent some of their ideas. This traditional design process was driven largely by the intuitive workings of the designer’s mind rather than an explicit scientific approach and it was often difficult to evaluate. The process also lacked formalization and the lack of formalization became synonymous with the concept of creativity (Oxman,2006).

"As one by one, all design tasks are becoming computational, some regard this as a danger, misfortune, or misappropriation of what design should be and yet, others regard it as a liberation, freedom, and power towards what design should be: conceptualization"(Terzidiz,2009). Digital media now provides realism and materiality to a field that was once largely intangible and could be hardly evaluated. More profound is how digital media has bridged the gap between architectural design and design production by a plethora of accurate and easily manipulated tools and processes. Computer-aided design processes now provide opportunities to create novel architectural forms and challenge traditional methods and processes in project conceptualisation and execution. (Norman and Tilder,2003).

Oxman in her paper on digital design theories stated that *"the emphasis on the influence of new media upon design processes and design thinking is a research contribution to this rapidly growing field" of design computation* (Oxman,2006).

3.2 **Design Computation and Creativity**

Design is a creative and hybrid activity, that depends on a proper blend of arts, science and mathematics for its successful execution. Although there are various definitions of the term creativity, most definitions imply the development of something new. "Creativity is often thought of as the ability to generate ideas that are both innovative and functional"(Alomar,2000). This simply implies that the novel product or design apart from being new, has to be satisfy a particular need. In the words of John C. Jones," a more profound notion of creativity is that of being able to change one's view of things, and of oneself, to the point of attempting something you thought impossible"(Jones,1992). In Architecture however, the term is relative as it depends on factors such as knowledge acquired, environmental factors, level of training amongst others. The level of creativity differs from designer to designer and is hinged on the ability to synthesize, explicate and clarify thoughts. The creative process as identified by Alomar is a sequence of four stages, namely:

- Preparation: Analysis, and description of facts and problems.
- Incubation: This is the phase where the designer ponders over concepts on an involuntary level.

- Illumination: Insight, new Ideas, assessment, Selection, and development.
- Verification: Approval and Action.

In Liu's conversations with Eisenman, Lynn and Mitchell on digital creativity, Liu pointed out that a creative designer, from a cognitive angle has many peculiarities. They include persistence, originality and the strong will to "make variation on a theme"(Liu,2001). In the three interviews, there was a common recognition of the computer as a tool that opens up possibilities for creativity. However, at conceptualization stages, there is a need to make quick ideograms, or sketches and the computer is considered slow for this due to the intricacies involved. He added that after conceptualization, the designer states the variables or principles and feeds it to the computer to predict possible outcomes.

Lynn on the other hand described creativity as the mastery of newness .So far most designers who employ digital technologies from his point of view are not creative, as they are still engaged in learning the new techniques and vocabulary offered by computational methodologies. However, there is potential for an "explosion of creativity" once it has been learned (Liu,2001).

Mitchell portrays a creative person as someone who has a motivation to do certain kinds of things. Technology removes possible barriers that could hinder the execution of ideas, opens it up and in turn speeds up the process (Liu,2001).

Similarly, Kocaturk realised, that creativity is enormously influenced by the immense variation in the set of tools available to architects today(Kocaturk,2008). The design approach of a designer that uses AutoCAD which is more 'traditional', differs from one who is proficient with geometric programmes like Rhino. More often than not, a designer that utilises geometric modellers has the freedom to create utopian ideas and as 'creative designers' are often associated with radical or utopian ideas, there is a tendency to infer that the latter is more creative than the former. This has generated debates on the definition of a creative design. However, it is important to note that the fear of the technology is not the issue, but the use of it. Technology is of no importance if wrongly used(Gazeki,2006). If technology is used to develop something a new design that does not solve a particular problem, such a product is only original and not creative.

Treib also cautioned that the "faustian bargain of the contemporary architect" with digital technology renounced a direct engagement with the craft of design. By this statement, he meant that the extensive use of digital technology by the contemporary architect had the tendency of having a negative effects on design (Treib,2008).

It is believed that, geometry provides the apparently common language through which architecture presumes to speak throughout history, across societies and over time (Lynn,1993). The departure from Euclidean geometry is the major characteristic of the 'intellectual revolution'. The intellectual revolution refers to the present era of digitization in which contemporary architects are constantly engaged in the search for unique design solutions.

Evolutionary processes of morphogenesis are the best known ways to create surprising and novel design solutions. In this context, a creative design solution is one whose characteristics were unexpected or not evident. The unpredictable, flexible and intelligent nature of computer simulated evolutionary technologies, provides designers the opportunity to create and represent forms whose workability is less dependent on the level of complexity. The increased understanding and fluency with non-Euclidean forms possessed by some designers that use computation methodology is attributable to the speed at which the computer produces iterations (Callicott,2001). These new techniques sponsor a richer appreciation of the designer's conceptual abilities (Burry,2011). Although, CAD/CAM has been instrumental to the modelling, fabrication, testing and evaluation of new architectonic possibilities , the initial spark comes from human creativity. The perceptual and cognitive abilities of designers cannot be automated as he remains 'editor' of the design process. Correspondingly, Oxman identified that "the control of digital processes as complex as they may be, is based upon interaction and reflection with the designer"(Oxman,2006). She added that the ability to devise, represent, execute and relate with explicit, properly originated representations of knowledge is the basis for the explication of cognitive processes in computational design.

3.3 Digital-Computational designs: Concepts, Tools and Processes.

For the purpose of this research, a review of extant literature will explore in the following sections, the underlying concepts of computational design as identified by various researchers in the field. It will also discuss the tools that are employed and the processes under the framework of Oxman's design components.

3.3.1 **Conceptual Content and Outcomes**

Kotnik (2010), in his publication, *Digital Architectural Design as Exploration of Computable Functions*, identifies three Levels of design computability namely, the Representational, the Parametric and the Algorithmic.

The Representational level is particularised by the use of the computer majorly as an electronic drawing tool (Kotnik, 2010). The use of popular CAD software available to most students and architects buttresses this assertion. They are prevalently used to produce and annotate basic drawings such as plans, sections, elevations and other traditional representation techniques. "On this level, the form of thinking is not regarded as computational as it still bears similarities to the paper-based manner of designing". **The parametric** level of design computation has become a common phenomenon in architectural praxis. It deals with the interdependency between various parts of the design, while on the **algorithmic level** "focus is on the development of computational design logic that is a sequence of algebraic, analytic and geometric operations for the manipulation of data and its transition into architectural properties"(Kotnik, 2010). The Parametric and Algorithmic levels he further explains are the true representations of computational design.

Earlier, Rivka Oxman(2006), proposed a taxonomy which includes five models;

The CAD models: These include two sub-classes, namely; the 'Descriptive CAD and the Generation-Evaluation models'. The former infers early CAD systems whose major particularities are describing designs through modelling and rendering. The latter refers to programs used in analysis of the geometrical models. A suitable analogy is the use of Gaussian analysis in the evaluation of the degree of curvature in complexly shaped elements.

Formation models: Involves the generation of forms through digital techniques such as scripting and operations such as NURBS to produce Non-Euclidean or Associative designs. Here, the designer is acts as the editor of the process due to the ability to modify factors that define the geometries. This is further sub- categorized into; 'Topological, Associative and Motion based Formation models'. Typical analogies of programmes that enable this form of design include CATIA created by Gehry Technologies and Generative Components by BENTLEY systems.

Generative models: This involves interplay with intricate computational mechanisms of form generation derived from principles of morphogenesis.

Performance models: This process of design is compelled by the desired performance of the eventual product. e.g. Thermal, acoustic or structural properties.

Integrated-Compound models: These are intended as a combination of the formation, generation and performance models.

Her classification was based on the conceptual content, the design processes applied. In an attempt to integrate Oxman's models into the levels of Computation, Kotnik(2010),likened the parametric level to formation models, algorithmic to generative models and representational level of computability to CAD models. He went on to explain that, although performance models play a crucial part in regard to the practicality of the digital design, they do not provide a new level of digital computability because, they are an hybrid of parametric and algorithmic processes. "The same is true for compound models, which are defined as a class of future paradigmatic digital design media"(Kotnik,2010).

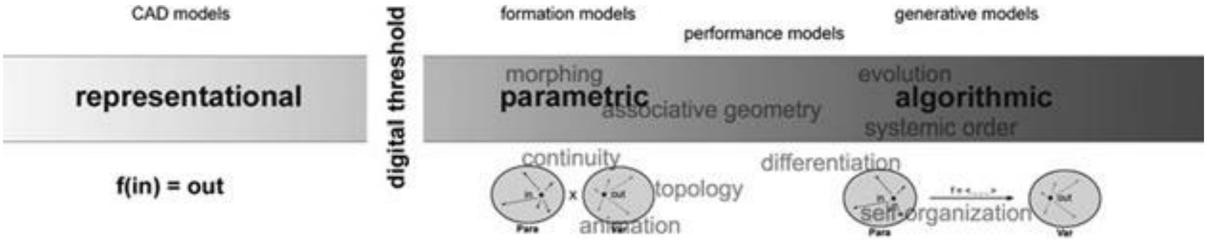


Fig 2: Levels of digital computability and Oxman's digital design models(Kotnik,2010).

Kolaveric (2003) defined computational architectures in terms of the conceptual content and end product as;

Topological architectures: This approach is characterised by the prevalent use of Non-Uniform Rational B-Spline (NURBS) to produce varied, yet coherent topological spaces. Surfaces and curves could be actualized by simply altering the position of control point and knots.

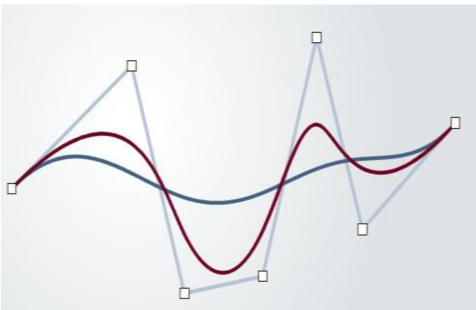


Fig 3: Nurbs line showing control points. Image© Miaumiau Interactive studio

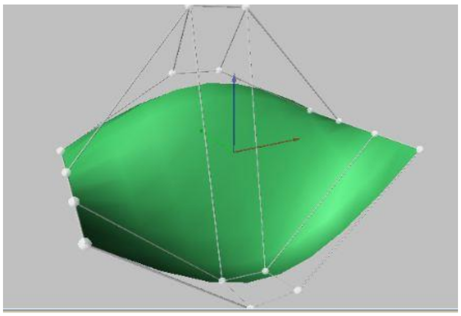


Fig 4: Nurbs surface showing control points. Image© rw-designer

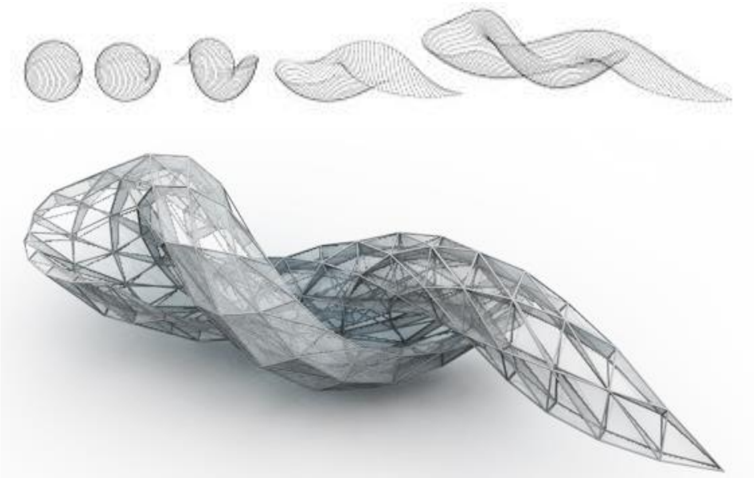


Fig 5: Transformation of a Sphere's topology
Image© Choma(2010)

Isomorphic architectures: Commonly referred to as blobs or metaballs, are a result of the synthesis of irregular forms with shared fields of influence. They are characterised by dynamic behaviours.

Animate architectures: Involves the use of animation software, which was originally a representational medium as a generative tool for form origination. The techniques applicable are Keyframe animation, Forward & Inverse kinematics, Dynamics and particle emission.

Fig 6: Lynn's Port Authority Bus Terminal in New York.

Metamorphic architectures: In this approach the manipulation of geometries can be realised with different techniques. They include, Keyshape animation, lattice deformation, path animation, amongst others. In Keyshape animation, a record of the stages of transformation is made and computed to produce an animation .

Parametric architectures: Here the design problem is defined by variables that can be manipulated to create a range of alternative solutions. The variables or constraints (objects) are usually referenced to each other, hence the term associative geometry or modelling.

Evolutionary architectures: In this approach to design, according to Frazer, "architectural concepts are expressed as generative rules so that their evolution and development can be accelerated and tested by the use of computer models

The first four listed above fall under Oxman's Digital -formation models and the Evolutionary is synonymous to Kotnik's Algorithmic level of computation.

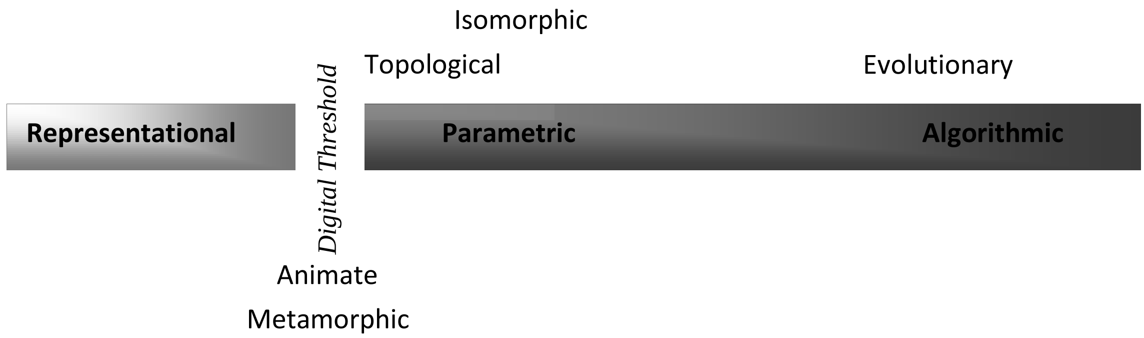


Fig 7 : Juxtaposition of Kolaveric's architecture with Kotnik's levels of design computation

3.3.2 **Digital Design Media**

Digitization is the main mechanism for much of the revolution been experienced in contemporary design. The success of Computational designs is greatly attributed to the tools available in this technological era. Architectural projects were customarily developed through a chain of linear processes, with design and construction totally estranged thus, resulting in information gaps (Alemany & Sousa,2003).The integration of Digital manufacturing into the Architectural design process has helped bridge the separated phases. The following sections explore the different medium through which digital designs are realised.

3.3.2.1**Classification of Digital Media**

For the purpose of this study, the tools that enable computation are further classified into two as:

Soft (virtual) tools

The virtual tools comprise of all the CAD and scripting programmes that enable the creation and visualisation of the designs. The 3D digital parametric model produced by these tools perform a core role: it serves as a document that comprises of the entire representations at an instance, as a converging point for various design consultants and specialists (Alemany & Sousa,2003).The ability to recover design histories, evaluate and manipulate them are advantages possessed by these programmes. In traditional, paper-based architectural processes, that involved the use of T-squares, Set-squares and pens, the focus was usually on the end product and abrupt modifications to designs were problematic or almost impossible(Rybczynski,2011).

Hard tools

These tools enable physical fabrication of digital models by utilizing both CAD(Computer aided design) and CAM (computer aided manufacturing) technologies. The CAM environment allows users to specify instructions for controlling CNC machines and related tools into machine able information. They allow designers create physical prototypes that aid in exploring design options during the design process, thus demystifying the traditional process of designing. According to Lawson(2006), "there are no steps in the design process. Everything is happening at the same time".

However the stage in which these tools usually come into proper use is referred to as the technical or production design stage. It normally involves the creation of detailed, technical specification drawings and documents that would enable accurate production of the design components. The reality of this stage affects the design process as the success of a design is often reliant on affordable construction costs. Other factors that are influential on the production design stage include the ease and speed of assembly, material selection amongst others. In digital environments, the geometric model is prepared for fabrication by disintegrating the model into constructible parts and converting to formats recognised by CAM tools for subsequent transfer to CNC machines. Geometries are usually modified in relation to the intended production process.

For flat shapes 2D fabrication is a preferred option. The techniques usually employed include unrolling surfaces, smashing, tessellation, sectioning and others. For solid forms 3D fabrication is prescribed, which is faster than the previous technique as the time required for assembly has been eliminated.

3.3.3**Digital Prototyping**

An important aspect that is not considered in the computational design approaches discussed earlier is the techniques involved in fabricating physical prototypes. "Prototypes are the most common formalism used to capture and apply architectural cases"(Kalay,2004). Rapidly created models or simulations are advantageous in testing designs during iterative design stages.

Architecture has been in the last few decades, strongly influenced by the product design world as fabrication is progressively becoming embedded in the design process due to increased accessibility of CAM tools . 'File to Factory' processes have enabled designers validate, iterate, and visualize from conceptual stages the possibilities of creating non-

Euclidean geometries. The new digitally-enabled processes of production imply that the constructability in building design becomes a direct function of computability(Kolaveric,2003). This is evident in the framework developed by Kocaturk, which identifies the interaction of extant design processes of representation, generation, with digital prototyping processes(Kocaturk,2008).

The categories of digital fabrication processes are:

3.3.3.1**Two-Dimensional Cutting**

This is the most widely employed technique of fabrication. "Various cutting technologies, such as plasma-arc, laser-beam and water-jet, involve two-axis motion of the sheet material relative to the cutting head, and are implemented as a moving cutting head, a moving bed or a combination of the two". Plasma- arc cutting originated from fusing CNC technology with plasma welding in the late 80's and early 90's(Renault,2007). The process employs a plasma torch at a temperature of about 25000◦c to cut steel and similar metals (Sacks& Bohnart,2005).The water-jet method emulates the concept of water erosion that occurs in nature. It is a more desired option for cutting materials that are sensitive to high temperatures. Water is sprayed or occasionally mixed with abrasive substances, at high pressure of about 20,000-55,000 psi (pounds per square inch) onto the intended cutting path of the object causing the material to erode(Lefteri,2007)." Laser-cutters use a high intensity focused beam of infrared light in combination with a jet of highly pressurized gas (carbon dioxide) to melt or burn the material that is being cut"(Kolaveric,2003).A form of laser cutting that uses a multiple-axis head to cut three dimensional objects is referred to as Laser-beam machining(Lefteri,2007).

Fig 8:Epilog Laser Cutter and Engraver at work. Image courtesy Fedtech.

Fig 9: Epilog mini 24 Laser cutter Image courtesy Cab Fab Lab Wiki

3.3.3.2**Subtractive Fabrication**

As the word implies, involves the removal or reduction of a solid block of material. Generally referred to as CNC milling, the reductive process can be achieved electrically, mechanically or Chemically. The milling can be axis, surface or volume constrained (Kolaveric,2003). The devices range from one axial router to multiple axial routers(four- five axes). Recently, this form of fabrication has been used to manufacture moulds for building components. An analogy can be found in the Villa Nurbs Project by Enric Ruiz-Geli, where customised moulds used in the production of the Ceramic Cladding was carved out using digital technology.

Fig 10: Digital Fabrication of Moulds for Villa Nurbs Facade.
Images courtesy Coud9.

3.3.3.3**Additive Fabrication**

This is usually referred to as Rapid prototyping. It is the most preferred option when speed is a priority. Charles Hull in 1986, developed the technology for production of physical 3D prototypes from digital information, however, the term 3D printing was introduced about a decade later when breakthroughs were realised by the Massachusetts institute of Technology(MIT) in the adaptation of 2D inkjet techniques to Hull's original invention. This technology has been adapted by shoe makers, the automobile and aeronautic industries for rapid production in their product design stages It has most recently been adapted for printing chocolate(Tahir,2012).

In the architectural design process, they offer geometrical freedom, as limitations arising from design complexities are minimal in this type of fabrication. The process "involves incremental forming by adding material in a layer-by-layer fashion"(Kolaveric,2003). It is also known as Solid Freeform fabrication. Common technologies include Stereolithography, Fused Deposition Modelling (FDM), Laminated object manufacturing amongst others . This method has several advantages over the subtractive which include a clean production environment and ease of use.

Fig 11: Z Corporation 3D printer and samples of prototypes
Images courtesy 3D systems.

3.3.3.4**Formative Fabrication**

This involves the reshaping or deformation of a material by the application of mechanical forces, restrictive forms, heat or steam. Example of this form of fabrication in product design include Slumping Glass and Metal Spinning.

3.3.4**Emerging Technologies**

3.3.4.1**Virtual Prototyping**

This is yet another technique emulated from the product design and automobile fields that allows the rapid prototyping of early design concepts. As design complexities increased, so was there a rising need for more sophisticated visualisation tools. As Kalay pointed out, this virtual prototyping is possibly the most vital contribution of computing to visual representation of design information, as it creates a "haptic and kinesthetic sense"(Kalay,2004). The invention of The sword of Damocles, a head-mounted display system(HMD), by Ivan Sutherland marked the birth of Virtual prototyping. The techniques available for this purpose are, Virtual reality(VR) and Augmented reality(AR). These are interactive technologies that permit users to virtually experience 3D designs in real time(Schodek et al,2005). Digital models and user interfaces are merged into a single immersive virtual environment. Apart from HMDs, other devices include a Hand- held BOOM display, a CAVE, virtual table, dome or panoramic screen systems.

Virtual Reality: VR technologies have become ancillary means of creating prototypes, as they provide a valuable simulation and visualisation environment for evaluating CAD models(Vince,2004). The user is fully immersed in a pseudo- environment engineered by the manipulation of image depths. Unlike traditional design methods, with this technique geometrical models can be visualised, 'felt' and edited with great ease and in limited time.

Multiple sensorial channels are engaged in this process. They include, visual, auditory, tactile and others.

Augmented Reality: This is a VR system that is more applicable to architecture and CAD in particular. It was created due to the need for interaction with the immediate surrounding whilst immersed in a synthetic one (Vince,2004). In this system, a transparent computer generated image is accurately superimposed on a real environment. AR technologies are relatively simpler than VR systems, as they supplement reality rather than replace it completely. AR techniques have the ability to add or remove objects from real environments (Azuma,1997). Users wear a head mounted display(HMD) with a stereoscopic video camera attached to it. This Camera captures the physical object, which is then displayed in the HMD and blended into the virtual model(Schodek,et al,2005).

Summarily, the three main peculiarities of AR are:

- The Combination of the real and Virtual.
- Registration of views in 3D
- Ability to relate in real-time

A most recent form of AR that is envisaged to greatly influence the design process is Spatial Augmented Reality (SAR). It projects in perspective, accurately generated computer images onto physical objects to augment their look and functionality. It bears similarities to Cave Automatic Virtual Environment(CAVE) as they use the same equipments and techniques. However ,unlike other AR systems it allows the users touch the virtual objects thus improving the experience(Furht,2011).

3.3.4.2**Robotic Manufacturing**

Here manufacture of prototypes is executed by robots. Industrial robots originally used by the automobile industry have become a fascination to Architects due to their milling, bonding, assembly and loading capabilities(Cokcan,& Braumann,2010). An example is the manufacture of roof members for the Great Court at the British Museum designed by Fosters where a robotic manufacturing process was developed to ensure the "tight geometrical requirements of position and orientation of each of the structural components every time"(Szalapaj,2005).

Robotic manufacture could be additive as seen in projects by Gramazio & Kohler Architects, subtractive when employed in milling and could serve as drafting tools. A most recent form of robotic production is Flight Assembled Architecture. This is executed by "quadrotor helicopters, collaborating according to mathematical algorithms that translate digital design data" into assembly information(Gramazio & Kohler,2011).

Fig 12: Robotic construction of a parametric brick wall. Image courtesy ETH.

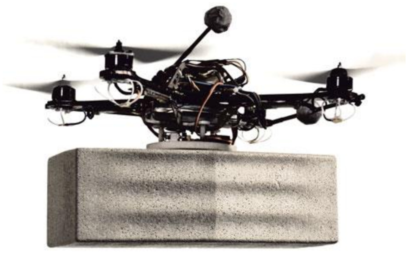


Fig 13:Quadrotor helicopter, carrying a brick. Image courtesy Gramazio & Kohler.

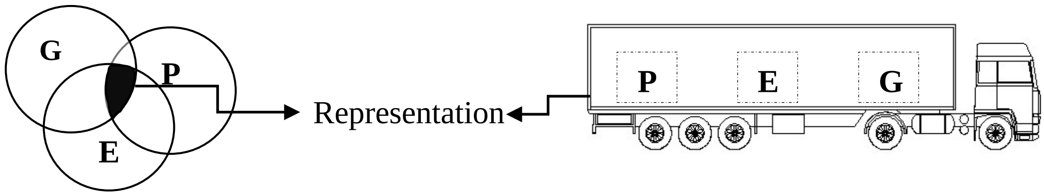
3.4 **Oxman's Components of Design**

With computational design, a lot of emphasis is placed on the process of design as it is means through which projects are realised. The rigour of the thought process is as much as a part of design as making shapes, thus necessitating the need to provide a detailed account of the nature of interaction with digital media and level of control the designer has over the process of design (Oxman,2006; Rybczynski, 2011).

Oxman proposed based on extant models of design, new models of digital design which addressed and explicated the differences between the evolving paperless design style and the traditional paper-based process. This was achieved by defining the peculiar and exceptional properties of the emergent designs. The components on which are models were developed are critically explored in the following sections and will inform the analysis of the data retrieved during this theses.

3.4.1 **Representation**

As identified by Kalay, is the vehicle of communication during design (Kalay,2004). Representation as a design component is a constant activity throughout the design process, as every change in the design has to be visually documented and shared with all the participants involved. Sketches, renderings, models, perspective views and photographs are essential modes of representation in the architectural design process. In traditional design methods that involved long periods to draft, representation served only as a communication tool and in no way improved or contributed to the process..With digital media, representational tools could serve as a means of finding form, or manipulating designs. This is greatly aided by the fact that models can be represented in various modes such as wireframe, solid or surface or conceptual modes.



Key

G:*Generation*

E:*Evaluation*

P:*Performance*

Fig14 : Illustration of the interrelation between the design processes, the centrality of representation and its role as a vehicle for communication

However, digital design environments vary in function, so some may be more suitable to a particular process than the other. Normal CAD models represent curves and surfaces as a series of line segments , while geometric modellers such as CATIA, Rhinoceros and Maya use explicit mathematical expressions to define entities (Schodek.,et al,2005).

3.4.2 **Generation**

Design has been referred to by renowned Architects such as Otto, and Kalay as a process of search; for problems and solutions. Generation is the process of developing and synthesizing the solutions or ideas discovered from the problem analysis stage. In the paper-based design process this required days , and commitment to the drafting board and tools. Interaction with the generated solution is different with digital media(Oxman,2006). Although computers have become vital components of contemporary praxis with digital representations utilized in all phases, the conceptual stage is one of the last areas to embrace the computer as hand sketches were considered sacred(Smith,2005).Recent computationally based designs focus on form finding at the conceptual design phase. Emphasis is usually on visualisation of sketches and ideas that make up the basic characteristic of the project."Designers have sought to develop computational environments that in one way or the other actually generate shapes according to pre-specified rule structures or other principles"(Schodek,et al,2005). Previously, Otto identified the use of computer optimization programmes in solution finding as a new form of "Self- Formation Process"(Otto.et al,1995). Design practices have different form derivation approaches attributable to the fact that the techniques and rationales for shape development vary from one programme to another. The frequently used tools in form finding is the use and manipulation of digital tools like lines, points, splines, loft and sweeps. Visually oriented computational tools based on descriptive geometry or other mathematical means of defining lines, curves and surfaces may also be used. Other methods include, repetitive algorithms, cellular automata, parametric definitions, "shape grammar" formulations, force density method and relaxation techniques. Some designers however, are considering the incorporation of time into form definition, in which the geometry changes in time based on some prescribed principles or external forces. While others seek to dissolve the usual barrier between virtual and physical worlds.

Digital fabrication is believed to now offer designers the opportunity to design through the production process as against the norm of beginning with form derivation(Gramazio & Kohler,2011). A typical analogy is the design of robotic walls, whereby the design concept was influenced by the availability of the tools required to make the its production possible.

Reverse Engineering: This is a valued and alternative method for conceptualizing and developing design proposals. It employs the use of physical and analog media(Kocaturk,2008). Firms like Frank Gehry & Associates pioneered the use of reverse engineering as a means of form derivation in Architectural practice. It involves the use of 3D scanning devices to digitally capture the geometry of existing objects or prototypes. The information is then transferred to a geometric modelling environment, where cloud of points are converted to surfaces through interpolation. These surfaces are interactively revised, edited and used to build a new digital model. This model is subsequently used in design development. The geometric softwares that support reverse engineering include 3D3, 3D Reshaper, ParaCloud, Geomagic Studio, Dezign works and others.

Structural Oriented Form-Finding Approaches: Techniques for structural form finding traditionally, were based on accurate, physical models, such as a network of hanging chains or minimal surface experiments with soaps films or stretch fabric. An instance is the continued use of Pneumatic scale models and hanging fabric systems by Heinz Isler to define the geometries of concrete shells. Other examples are found in the hanging models by Gaudi where force diagrams were translated into forms(Kilian,2006) and in experiments by Frei Otto and Bodo Rasch.

The most commonly employed computational techniques based on this approach include *the force-density* method *the dynamic relaxation* technique.

3.4.3 **Evaluation**

"Evaluation is a direct consequence and derivative of the uncertainty that is inherent to the process of design"(Kalay,2004).It involves the rational and logical evaluation of internal conflicts. This process constitutes the feedback part of the design cycle. Solutions proposed are compared with the goals, constraints and opportunities developed during generation.

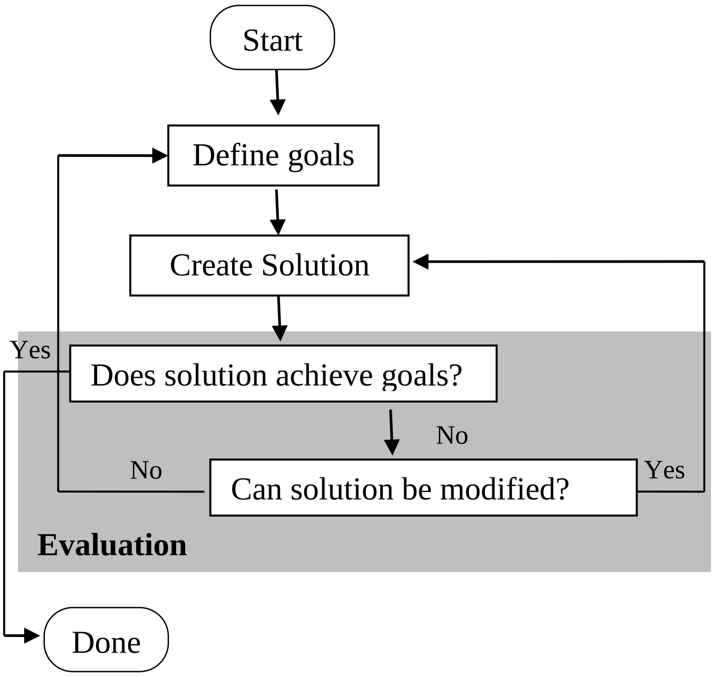


Fig 15:"The iterative structure of the design process, and evaluation's central role"(Kalay,2004).

From the illustration by Kalay above, it is evident that all questions concerning the created design solutions are assessed during the evaluation process . If the design solutions meet the stated goals and can be modified then it is successful otherwise the goals are redefined and solutions recreated. Evaluation normally occurs in the design development stage and requires more time and effort than the other stated stages. In this stage design intentions are developed and evaluated technically. The modelling at this level is mathematical and very precise, because, the main parameters of the design are defined and assessed. Dimensions, and analysis of the model's structural, thermal and material characteristics is carried out in preparation for production of prototypes(Schodek.etal,2005). Design development frequently involves the collaboration between various specialist, thus the need for add-ons such as structural analysis programmes. These ensure smooth transitions between digital expression of design ideas and their analytical evaluations. Programs that enable this rigorous activity of development and assessment include, MicroStation, Revit,CATIA, Pro/ENGINEER, Kangaroo Physics, SolidWorks and others.

3.4.4 **Performance**

This is also an evaluative act that examines the context of design and the programmatic orientation of the design (Oman,2006). Kotnik however, admonishes that performative design strategies could limit architectural thinking to parametric changes only as it tends towards optimising and being economic(Kotnik, 2010). With digital media designers now have the ability to envisage the future performance of whatever geometric forms generated.

3.5**Design Processes and Digital media**

This research attempts to give a generic schema of the tools utilized and their relationship with the respective design components.

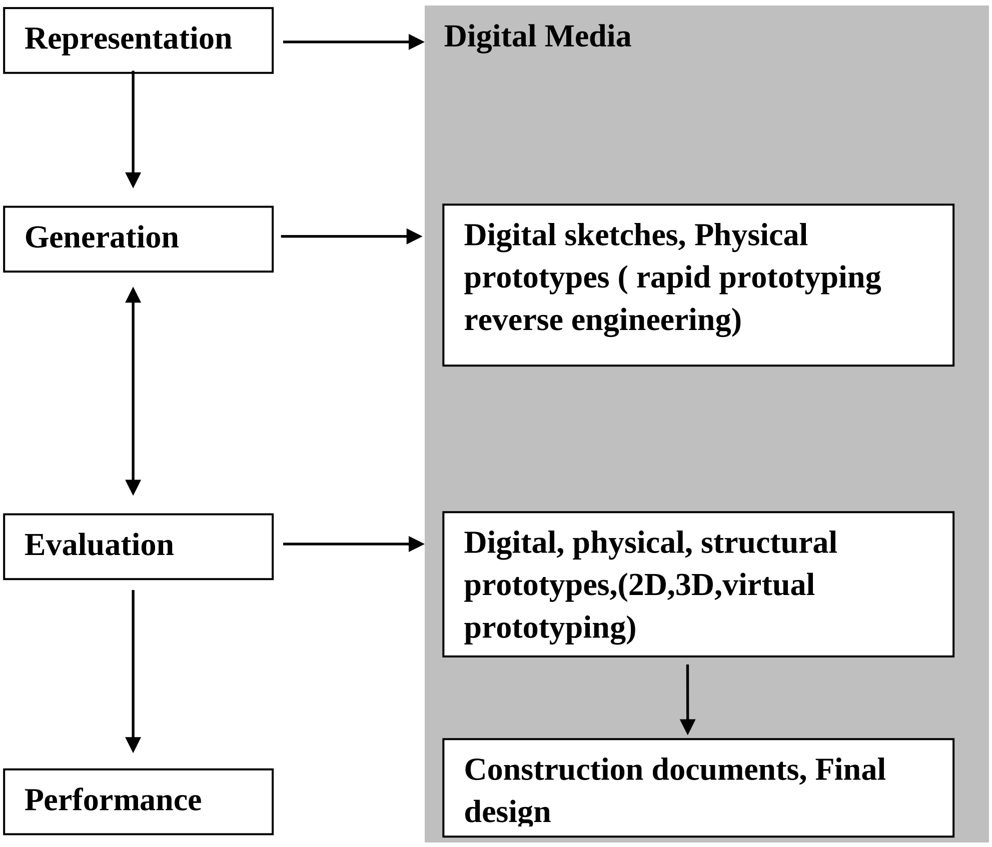


Fig 16: Illustration of the use of digital media during the design process.

In the generation phase as illustrated above, forms are derived from digital sketches or conceptual models produced by rapid prototyping techniques. Then in the subsequent stage of evaluation, various methods of prototyping are utilized in creating models or drawing that would in turn be assessed and analysed. Evidently most of the tools are employed during the generation and evaluation phases.

3.6 **Summary**

Following the overview of design processes and the definition of digital computational designs, the relationship between design computation and creativity was explored. Contextual contents by Kotnik, Oxman and Kolaveric were then discussed. This was followed by a classification of digital tools and the various prototyping methods peculiar to digital-computational designs. Emerging prototyping techniques were also discussed and pictorial representations provided. Digital design processes were then discussed using the components of design as identified by Oxman(2006). The chapter was concluded with an generic illustration showing the use of various tools in respective stages of the design process.

Chapter 4

Case studies

4.0 Introduction

This Chapter is a compilation of recent representative designs and research work from contemporary design practices. Each of the cases documented in this chapter demonstrate the way and scale in which these practices apply their technical, creative and organizational skills to the resolution of design problems. An insight is gained into the processes of design and the extent to which computation supports and aids the progression of the design ideas is analysed. The selected cases are analysed using the identified components of design in Oxman's publication that was discussed in the previous chapter.

4.1 Analysis of Case Studies

4.1.1 Aedas Computational Research and Design Group.

Amongst the foremost practices in the world today and founded in 2004, Aedas is devoted to research and pioneers initiatives across disciplines in the development of design methods through computation and parametric tools that help enumerate, envision and control spatial, environmental and economic factors of a design.

The focus of Aedas R&D Group is on three main areas of research: Computational Design, Advanced Modelling, Sustainable Design. It leads in-house as well as cross-disciplinary industry initiatives, offering thought leadership and motivating innovation throughout the practice. The creation of parametric models and simulations by the group attracts creative participation and offer the starting point for coordination through interactive representations of a design. This approach to design contributes to their understanding of occupancy patterns and perception, energy use of buildings and the lifecycle impact of early design decisions. The team's involvement in all stages of structural, mechanical, spatial and quantitative coordination allows for inspired architectural solutions that meet implicit and explicit performance criteria.

4.1.1.1 **Taipei Nangang Office Tower**

This is a proposed 18 storey tower designed by the AEDAS Beijing Limited. The inspiration for the design was drawn from river pebbles as they present opportunities to propose inimitable aesthetic designs. The concept was developed using a flow of parametric tools that ensure flawless information delivery. Described in the subsequent sections are the processes through which the design was realised.

Representation

The modes of representation employed ranged from the use of manual sketches to virtual 2D and 3D images. A parametric workflow that comprised of the use of Rhino, Rhino plug ins and Revit Architecture served as a vehicle for communication at different design phases. Demonstrated below is an illustration of the relationship between the design environments

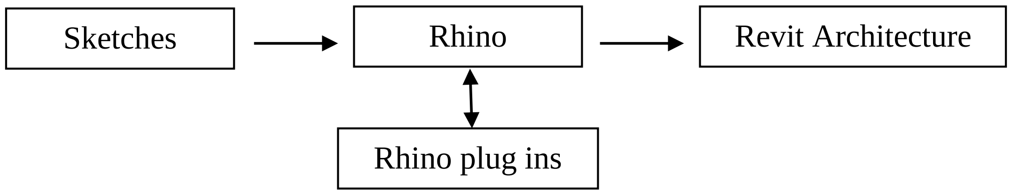


Fig 17: Illustration of the modes of representation and their relationships.

Generation

Initial sketches of river pebbles were created, and a vertical green wall proposed to characterise the facade of the building. The green wall was intended to serve as a 'dry filter', a breathing facade for the massive tower.

The building mass was subsequently designed and generated in Rhino while the geometric information was created in grasshopper .

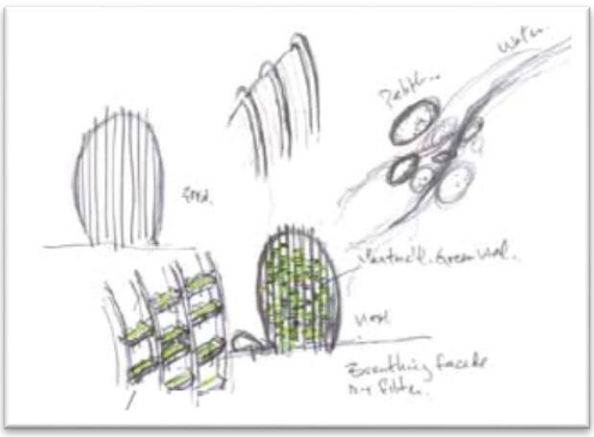


Fig 18: Initial Sketches
Image ©Aedas(2011)

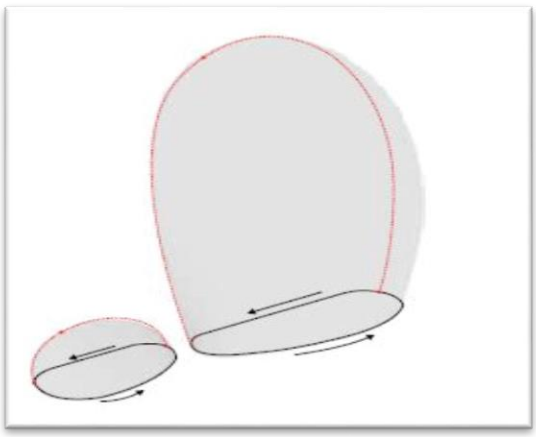


Fig 19: Rhino generated form
Image ©Aedas(2011)

Facade Development:

The leaning nature of the building form made complicated the use of the intrinsic UV information of the geometry. As a result of this difficulty, a new grid system had to be defined which was driven from the floor height and a sub-divided column grid. The floor plate profiles were extracted with levels defined by grasshopper.

The connections between the grid systems and geometry, produced the information needed to define facade fins, mullions, spandrels and curtain wall panels. The use of grasshopper proved very beneficial as the information obtained from the building geometry are all associated. Therefore, when the design of the mass was going through a change, it was faster and more effective to re-evaluate the design outcome.

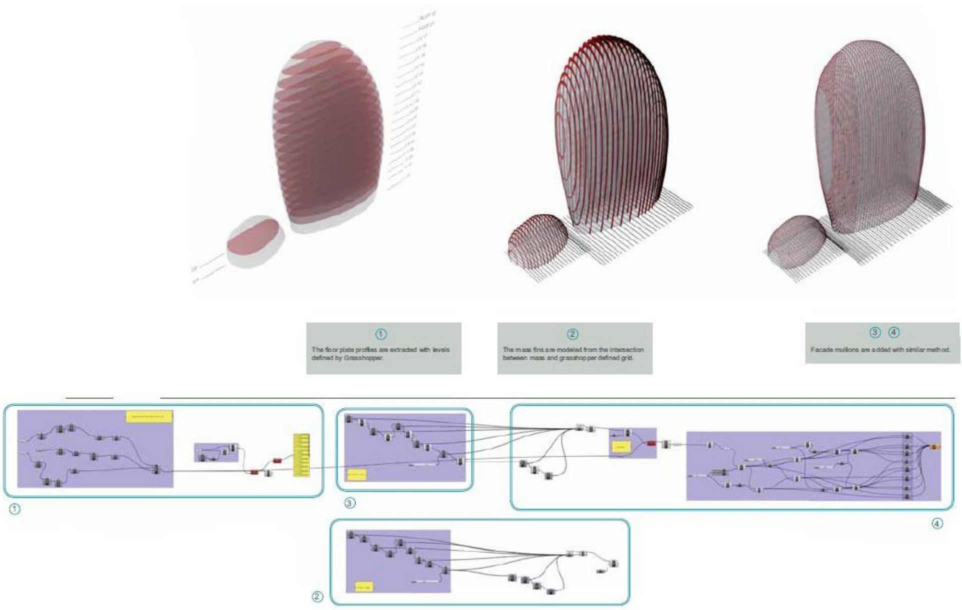


Fig20 : Stages of generation of the building's facade in grasshopper for Rhino

Evaluation

Surface Panelization through Rhino Panelling tools

The surface was rationalized using Rhino panelling tools to create the facade panels. The panel numbers and sizes were evaluated through Rhino Panelling tool add-on. UV grid points were manually defined and placed on the base surface to generate the panels. The ability to develop the panels physically was then evaluated in grasshopper.

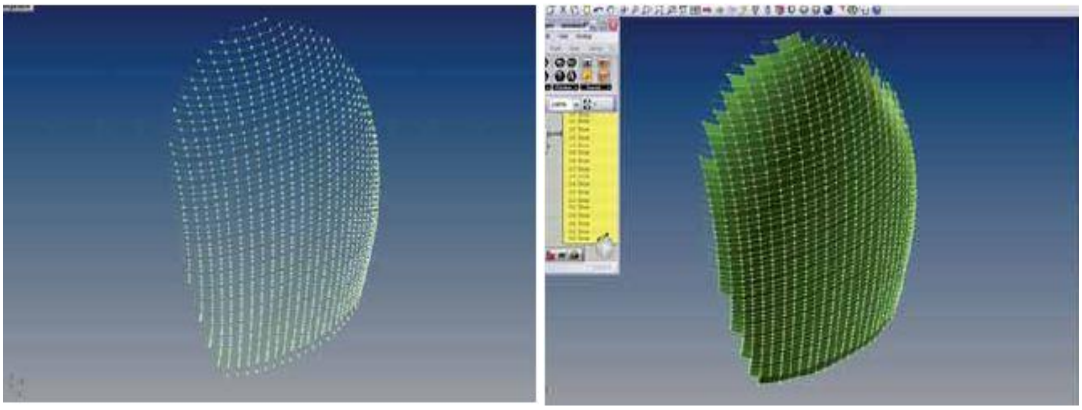


Fig 21: Surface panelization and evaluation
Images© Aedas

Verification

Delivery Production through Autodesk REVIT:

3D information from Rhino was exported to Revit as a SAT file to be used to generate drawing sets such as plans, sections, and elevations. This preserves the geometric information of the massing model. Information within Revit model automatically updates itself according to the newly imported Rhino mass.

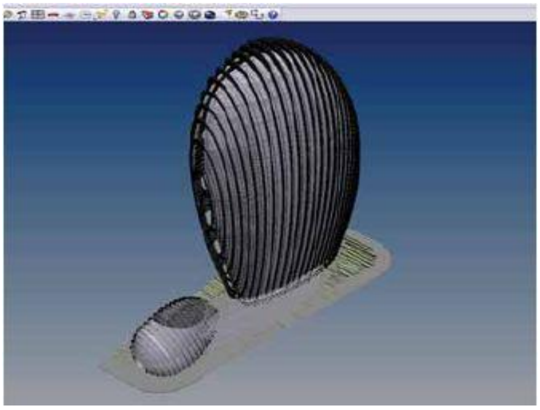


Fig 22: Complete building form in Rhino
Image© Aedas.

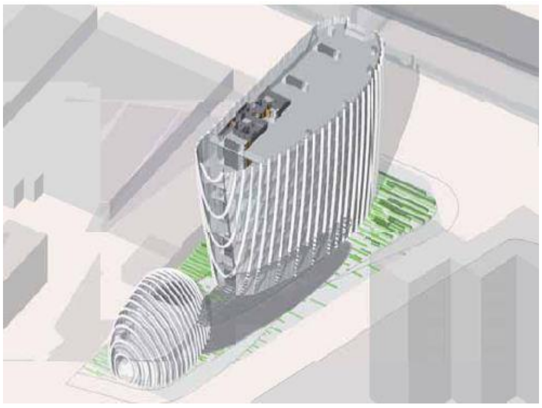


Fig 23: Imported SAT file in Revit
Image© Aedas.

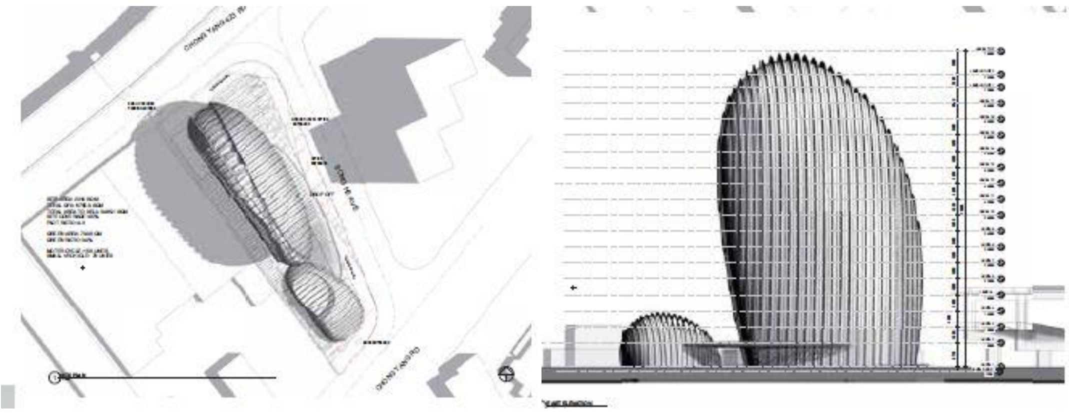


Fig 24: Generated 2D drawings
Image© Aedas.

Performance

The flawless transfer of information between the digital environments and their inherent compatibility preserved the conceptual content on which the design was conceived. This made the explication of the designer's idea successful. Revit was very helpful in providing all the details necessary for construction of this office tower whose contextual and programmatic orientation was to serve as 'an incubator of ideas'. The breathing envelope creates diversity, flexibility and controls the building temperature, thus resulting in a sustainable design as the aluminium fins control the amount of sunlight that penetrates the building vertically, while the planters provide shading horizontally and filtering the air that enters the building (Archiscene, 2011).

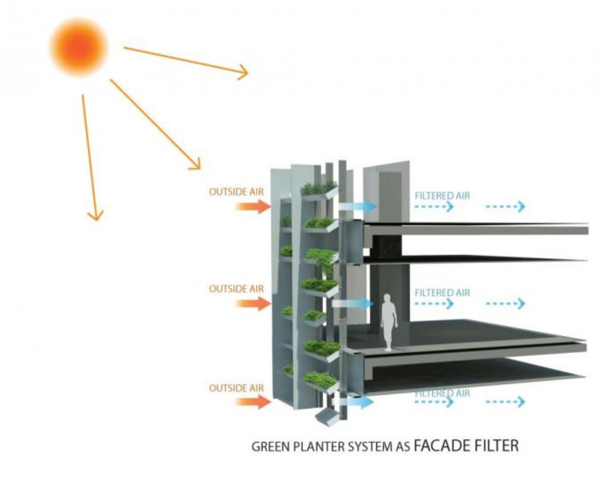


Fig 25: Illustration of the performance of the building facade image© Archiscene 2011

Fig 26: The final design image© Archiscene 2011

4.1.2 **Gramazio &Kohler**

The practice led by Gramazio and Kohler are pioneers of the concept of digital materiality. Other methods apart from drawing are employed in design. Exploration of the potentials offered by computational design methods and digital fabrication is used to complement traditional design and construction. Documented in the following section is one of the projects executed.

4.1.2.1 **Vineyard Gantenbein Facade (Robotic Masonry)**

Vineyard Gantenbein is a grape processing plant situated in Flasch, Switzerland. The initial proposal for the facade was an offset of bricks within a concrete skeleton. The openings within the bricks allowed direct sunlight into the fermentation room which not functional as the intensity of the light could have adverse effects on the process of fermentation. Polycarbonate sheets were installed inside to shield against wind. The ballustrade of the roof was formed by the bricks on the upper floor. The construction had already commenced on the project which was originally designed by Bearth & Deplazes Architects, when Gramazio & Kohler Architects were commissioned to design its facade. The following sections explores the stages of design.

Fig 27:Exterior Views of the Vineyard Gantebein.

Inspired by digital fabrication, the brickwork of the vineyard's new façade bears resemblance to a massive basket filled with grapes. At a close up view – in disparity to its graphic effect at a distance – the sensual, textile softness of the walls dissolves into the materiality of the stonework. The viewer is astonished that the soft, round forms are actually made up of individual, hard bricks. The façade comes into view as a solidified dynamic form, in whose three-dimensional depth the viewer's eye is invited to wander.

Representation

The representation of the design process was entirely digital. The Maya environment and the scripting language embedded in it allowed the simulation of the design concept and enabled the creation of a design pattern that is not achievable by hand(Gramazio& Kohler,2008).

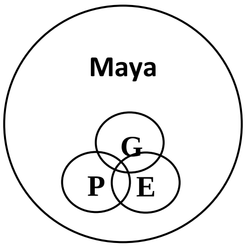


Fig 28: Illustrating the interrelation between the processes within Maya environment.

Generation

The already constructed concrete frames were interpreted as a grape-filled basket, to create the generation process that would drive the facade design. Gravity was subsequently simulated to closely fill the virtual basket with falling spheres representing the grapes. The resultant views from all sides were converted into pixels or digital information to represent the rotation of individual bricks.

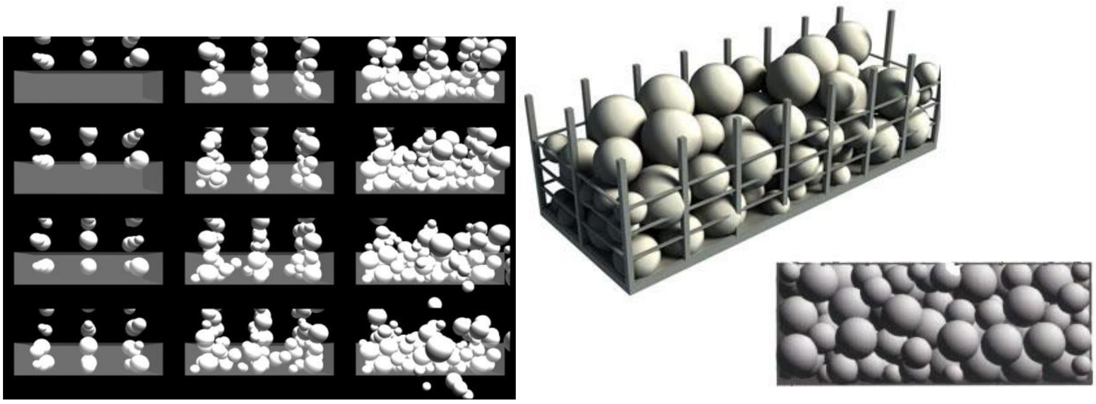


Fig 29:Falling Spheres & Basket filled with grapes.

Due to the inability to access the actual scripting details for this project during the course of this research, a similar method that produced the same results in Rhino Script which was demonstrated at the Digital Architectural Design Studio, University of Salford, by **Mario SASSONE**, an Assistant Professor at the Department of Structural and Geotechnical Engineering, Turin Polytechnic, (ITALY) is documented as follows.

The raster image of the closely packed spheres was converted into a matrix of numbers representing the gray scale level of each pixel, then a file name generated. The width and height of the pixels were also specified, after which input and output file systems were assigned to handles in order to create objects in the Rhino shell. The ASC II coding of the gray level was then converted to an 8bit number, and the value added iteratively to the line string. It was subsequently sent to the Rhino shell.

The information derived from the numerical interpretation of the image pixels were then linked to the code as a guide for the parametric generation of the wall.

A set of rules were established to govern the parameters such as:

- The width, height and depth of the block units
- The thickness of the mortar
- Wall height and width.
- Starting point of the wall

The wall height and width were then multiplied with provisions made for the mortar thickness. Various array operations were successively performed and the bricks rotated in relation to each pixel representing the spheres. A detailed version of the script is attached to the appendix of this thesis.

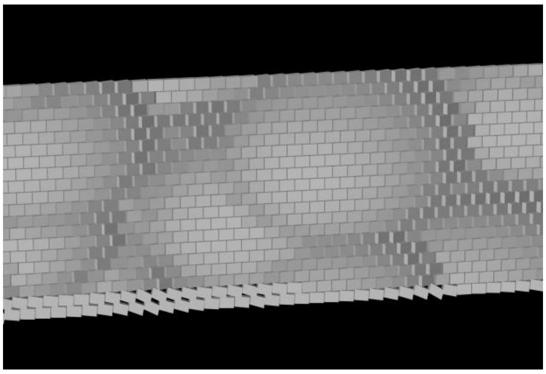


Fig 30:A sample of the 'grape wall' generated at the DAD studio.

Evaluation

The ability to feed the design algorithm directly to the robot during construction, enabled continued design of the facade till the last minute as there was no need to produce further fabrication drawings.

In a quest to speed up the production process for the 400 square metre façade, an automated procedure was developed for application of the dual element bonding agent. Due to the difference in the angle of rotation of each brick, each one had a dissimilar and distinctive overlap with the brick underneath it, and consecutive one under that. A method was established in conjunction with the brick manufacturers in which four parallel bonding agent paths were applied, to individual bricks, at pre-defined distances to the mid axis of the wall element. Load tests performed on the first elements manufactured revealed that the bonding agent was so structurally effective that the reinforcements normally required for conventional prefabricated walls were unnecessary.

Performance

Apart from achieving the desired result for the facade on the exterior, in the interior, the daylight that penetrates produces a gentle, yet bright environment. Looking towards the light, the design becomes apparent in its modulation through the open gaps. It is superimposed on the image of the landscape that glimmers through at different levels of definition according to the perceived contrast. Robotic production techniques developed by the duo , Gramazio and Kohler at the ETH Zurich department of Architecture enabled the design and construction of a wall that was permeable to the desired amount of light and air required for the fermentation process.

4.1.3 **The Hangzhou Olympic Stadium and Tennis Center**

The Olympic Stadium and Tennis Center which was designed by NBBJ in collaboration with CCDI, is situated in Hangzhou, China. With a seating capacity of 80,000 and 10,000 respectively , the facilities are scheduled for completion in 2013 as part of a sports and entertainment city featuring other recreation facilities . The Stadium and the Tennis Center share a similar architectural vocabulary of repetitive sculptural truss geometries which make up the external forms.

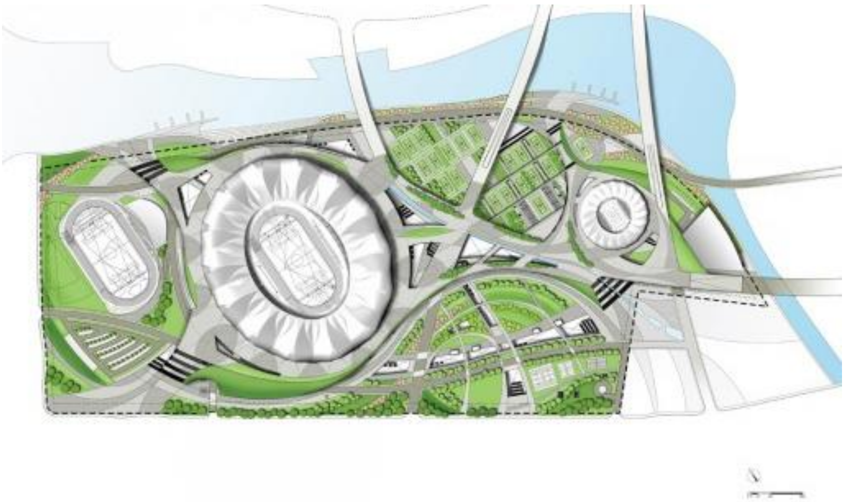


Fig 31: Views of Hangzhou entertainment city
Images© Arch daily (2010)& Miller(2011)

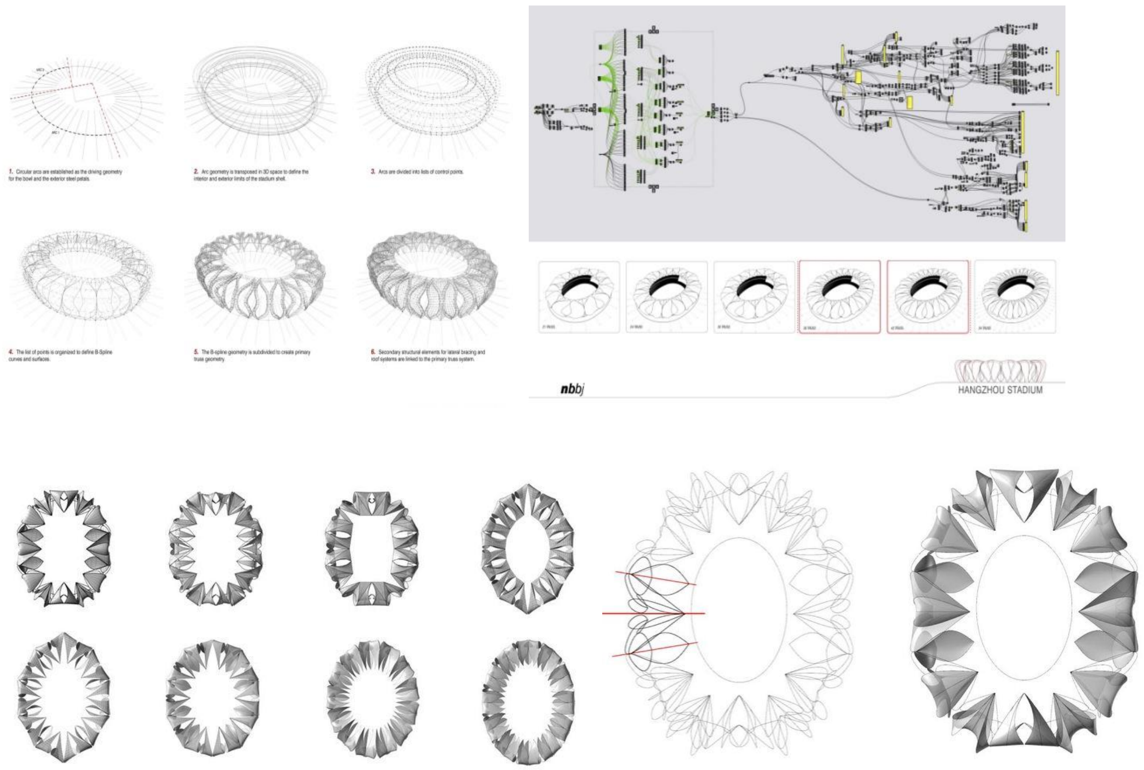
Representation

Solutions to challenges encountered by the design team, during the process of design were facilitated by the customization of tools and implementation of new computational methodologies. The main features of the design were conceptualized, stimulated and documented with the use of an integrated parametric system as explored in the following sections of this study.

Generation

The study of 3D, symmetrical B-spline patterns informed the development of an initial geometric concept from, consequential from a thorough copy-mirror process about an elliptical stadium shape (Miller,2009).

The design concept for the envelope was based on modularity of sculptural, petal-like steel trusses housing the technical systems. The preliminary form generated, limited the addition of complexity to the envelope at later stages of the project thus necessitating the creation of a point cloud system that served as control points to parametrically manipulate the edge curves. The symmetry of the geometry allowed the luxury to develop one quadrant at this stage. This was beneficial as it aided the computation process by enabling improved and faster iterations. The design team were able to explore and study different design variations whilst considering factors such as aesthetics, drainage, parameters for shading , structural performance.



Figs 32 a b c & d: Form generation and exploration process of variations of Hangzhou stadiums' envelope. Images© Miller(2011)

Evaluation

Due to the integral connection between the geometry and the structure, a very close relationship between the NBBJ design team and the CCDI structural team was essential to successfully co-ordinate the 3D steel model.

A grasshopper algorithm was developed to facilitate the conversion of the geometry into a wireframe structure, compatible with the engineer's analysis tool. This enabled both teams minimize the time that would have been required in creating an engineering-specific model.

The UV co-ordinates on the petals were employed in panelization. The parametric algorithm also had surface analysis integrated in it to test for the planarity of each petal.

Kangaroo physics, an investigational physics engine, was used in combination with a visualisation script to envision, tensile, compressive forces and areas of maximum stress. Having this integrated at the early stage of design also improved the collaboration between the structural and design teams.

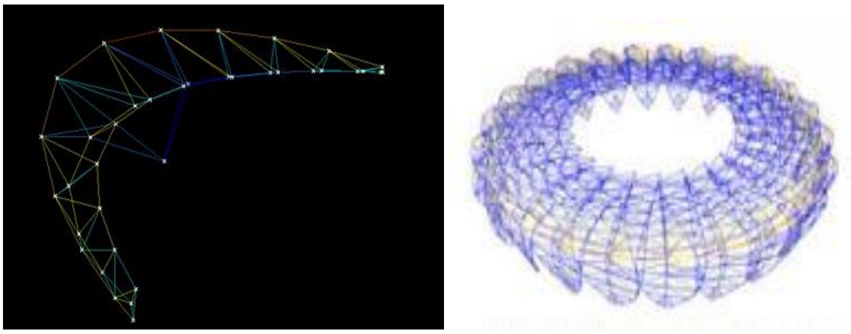
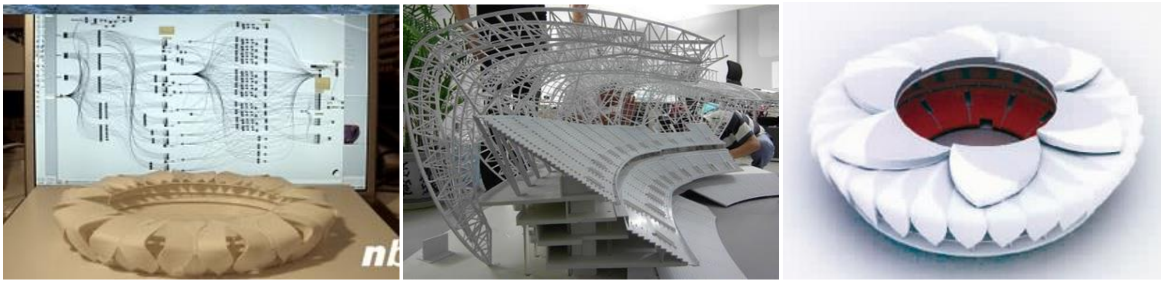


Fig 33: Evaluation in Kangaroo Physics
Images© Miller(2011)

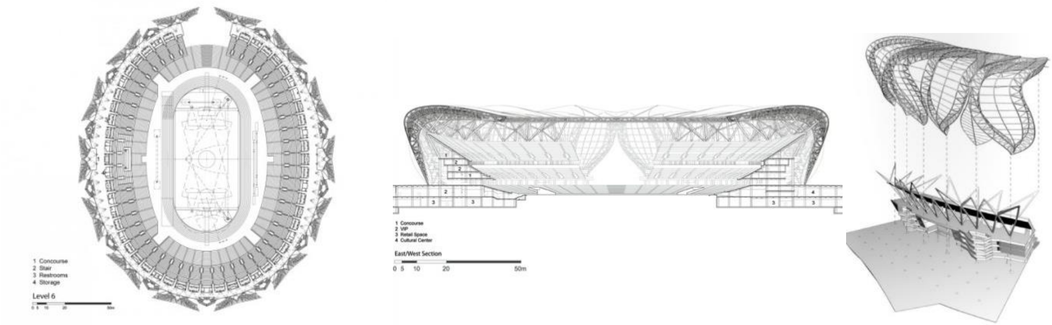
Grasshopper was used at all levels of the project. Apart from its use in form derivation and structural design, the algorithm facilitated the co-ordination with other external documentation tools. 3D information was translated into Autodesk Revit which was in turn used to generate documentation sheets. The grasshopper script, also automatically unrolled the surfaces and provided a spreadsheet with information on surface curvatures.

Performance

Design computation enabled the successful delivery of stadiums, with a new vocabulary. The petal apart from characterising and enclosing the stadiums , house the technical facilities.



Figs 34 a, b, & c: Physical, Structural and digital prototypes
Images© archiprose(2010)&Hi centre (2010)



Figs 35 a, b, & c: Detailed orthogonal construction drawings created in Revit.
Images© NBBJ(2010)Miller(2011)

4.2 **Additional Case Studies**

Due to limitations encountered during this study, additional cases where studied ,to further strengthen the validity of this research. One represents an experimental project and the other a contemporary blob(Isomorphic architecture). The success of both projects is majorly attributable to robotic manufacturing processes amongst other factors.

4.2.1 **Research Pavilion ICD/ITKE**

The Research Pavilion is the brain- child of the University of Stuttgart's Institute for Computational design in collaboration with the Institute of Building Structural Design. It is a temporary structure that demonstrates the advancements in the material-oriented approach to design computation, material simulation and robotic prototyping processes in architecture. It bears similarities to the design approach of the Gantenbein vineyard.

The bending-active geometry was constructed with elastically bent plywood strips that were fabricated by robots. The changes in the structure's material were documented during the operation and a 3D scanner was used to measure its geometry in order to validate its structural performance.

The approach employed in this case is an alternative to the commonly used computational design approaches because, the goal of the research was to dissolve the barrier between virtual and physical worlds as discussed earlier under form generation. This is attributable to the fact that the design process as stated by Menges, "unfolds morphological complexity and performative capacity from material characteristics and fabrication logics without differentiating between form generation and physical materialization process"(Menges,2012).

Representation

An integrated script served as the environment in which the computation design and FEM model was generated. The rest of the information was represented by the robot during the construction of the prototype. A third mode of representation is the point cloud dataset derived through full-scaled scan and geodesic measurement of the built prototype.

Generation

The physical behaviour of the material directly informed the creation of the form as the structure was shaped according to the elastic bending attributes of the birch plywood strips. The structural capacity of the pavilion was increased and maintained by the locally stored force in the bent areas of the strip. 80 individually peculiar strips were constructed from 500 geometrically unique parts to prevent concentration of bending moments on local points.

Evaluation

The model was analysed based on a FEM simulation. The level of structural detail and unique characteristics inherent in the prototype enhanced the comprehension of the internal stresses that occur as a result of the material's deflection in relation to external forces such as wind and snow loads. This information is beneficial in predicting the durability of the other elastically bent wood constructions.

Performance

The integrated design environments enabled the integration of design computation and materialization, hence achieving the research goal.

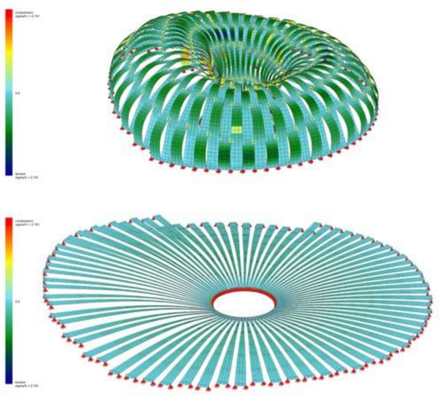


Fig 36 : Showing the FEM simulation image© ICD Stuttgart.

Fig 37: Showing the completed Pavilion image© Schleicher ITKE

4.2.2 **Kunthaus Graz (The Friendly Alien)**

Designed by London -based Space Lab Architects in collaboration with Architektur and Bollinger + Grohmann (structural engineers), the Kunthaus graz is a museum for contemporary art, situated in Graz, Austria. The building is a bluish, transparent, jelly looking, contemporary blob made of foam glass and acrylics following an arbitrary curve. Its main feature is an organic mono-structure with several organic nozzles characterizing the roof. These nozzles incoprate louvers, filters and diffusers in order to control the light quality and include artificial light sources to supplement or override the natural lighting (Cook et al., 2004). The design process is analysed in the following sections.

Representation

A conceptual physical model was initially created after which a digital model was produced. Geometric modelling environments were extensively used in the design process. The programmes utilised include Rhino for form generation, CATIA V5 and ProEngineer. The form was visualised in different modes from 2D wireframe to solid 3D views especially when the truss system was designed.

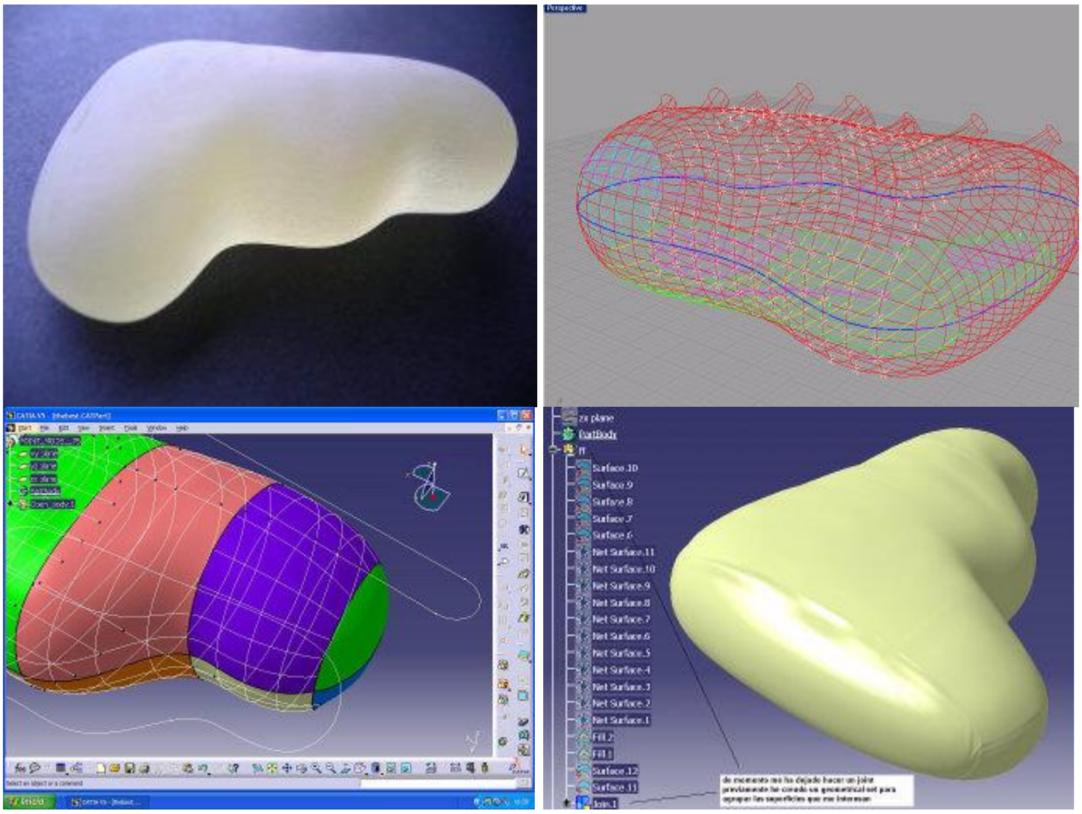


Fig 38 a, b, c,& d : The modes of representation employed in the design process

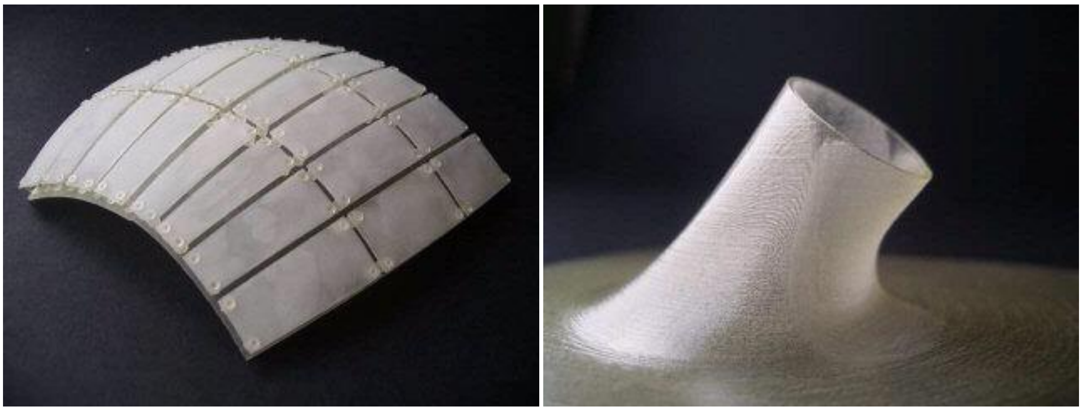
Generation

The basic shape of the building was determined by various factors. They include the volumes of the interior spaces, the technically possible spans, the prescribed distance to neighbouring buildings amongst other factors.

In the design process generation and evaluation were run concurrently due to the complexity of the proposed geometry. Initially, work began by using a physical model, then a subsequent creation of a potato like Nurbs surface using a 'volume model'. The digital model was developed to provide a common basis for both structural evaluation and architectural design(Cook et al., 2004). However, due to the double curved nature of the shape, further form exploration was suspended in order to explore solutions to how the form would be fabricated.

Evaluation

Techniques for building double curved surfaces considered were the 3dl system used in manufacture of ships and casting. The 3dl option could not support the manufacture of a double curved surface that was also transparent . The casting technique was an expensive option because, it implied the production of special moulds and could not precisely follow an arbitrary curve.



Figs 39 a & b: Detailed models of Facade and roof elements

Another technique explored was the use of moulds robotically cut out from Styrofoam blocks. This proved very fast, beneficial and precise because, the Styrofoam was easy to cut. However, the use of the material as a mould had shortcomings, such as the grainy nature of its surface and its low resistance to heat thus making it unsuitable to hold glass which require high temperatures. The solution was discovered in the use of thermoplastic materials (Plexiglas). A 5 axis milling machine was proposed to create customized mould according to the curvature of each panel. The decision to use Plexiglas was driven by the process of production envisaged.

The main goal of exploring construction methods during form generation was to minimise the waste of materials, thus necessitating the need for a system that worked seamlessly on all sides. The design solution was the use of parallel convex arches to create an orthogonal system unto which the structural grid and facade were subsequently superimposed.

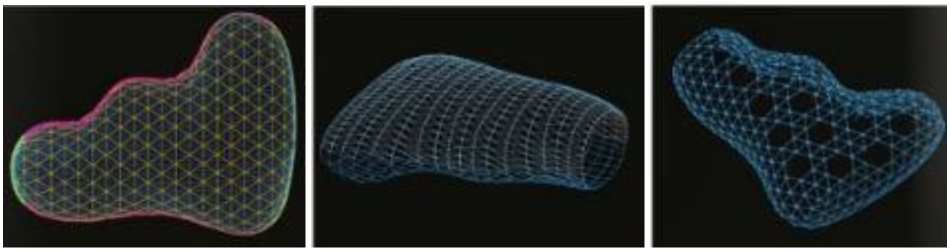


Fig40 a, b &c :Stages of development of the structural grid system
Images ©

The digital tools enabled exploration of alternatives and the eventual discovery of the most appropriate means of manufacturing the facade elements and the most appropriate structure to which they would be connected. The completed CAD design generated a 3D model suitable for prototyping(Cook et al., 2004).

Performance

As Pakesch identifies in the starting points and goals for the Kunthaus graz, "architecture takes on a special significance with regard to the building's contextual and programmatic orientation"(Cook et al., 2004). The design functions as an architectural landmark as well as an exhibition centre which it was intended for.

Summary

In this chapter, five projects studied were analysed according to the representation, generation, evaluation and performance criteria. The projects analysed revealed the design processes and techniques employed by the diverse practices. the Taipei Nanang office tower design began at the lowest level of representation and generation, while the other projects were mediated by computational methods.

Chapter **5**

Discussions

5.0 **Introduction**

Although the cases analysed in the previous chapter were selected from various practices in order to validate the objectivity of this research, there is a common theme; the use of the computer to communicate ideas, rationalize and optimize geometries. Anomalies to this rule are the design processes of the Vineyard Gantenbein facade and the Research pavilion, where the geometries could only be verified or measured after the design or actual manufacture of the prototype. They represent totally computer mediated designs, owing to the fact that the concepts could not be accurately represented nor constructed manually.

In this chapter, the projects are discussed point by point based on the hypothesis statement.

5.1 **Comparative Analysis of Case Studies**

The numerous advantages of computation range from the ability to preserve design intentions free of any specified geometric repetition to the elimination or reduction of costs associated with generate-test-discard models of design practice . However, the grounds for comparison in this thesis in relation to the aim and hypothesis , are based on the *design solutions*, *design speed* and *creativity*.

5.1.1 **Design Solutions**

Design solutions generic to all the cases studied is the exploration and comprehension of the fabrication or construction of prototypes or actual buildings respectively. However, a detailed account of the design solutions identified by the designers in each case is presented.

In the case of the Taipei Nangang Office Tower by Aedas Beijing Ltd, the major design solution was the use of grasshopper to resolve the difficulty encountered during panelization of the building facade due to the leaning and curvy nature of the geometry. The model information was thus extracted using grasshopper Plug in, and the mass fins modelled from the intersection between the surface of the geometry and the grasshopper defined grid. A similar method was employed in adding the facade mullions.

Gramazio & Kohler defined a new use for brick as a building element. Apart from the new aesthetic value that was created, the openings between the blocks enabled trickles of daylight into the building. The design process also reduced the cost of design as there was no need for printed copies of construction documents and other activities associated with the 'traditionally' executed designs. The construction cost of the project was significantly lowered also as the amount of bricks and materials was already predetermined and all forms of human errors encountered during construction eliminated by the use of 'robotic masons'. Similarly the research pavilion at ICD, demonstrates the feasibility of a top-down design and engineering approach. The two projects are testaments to the fact that digital fabrication enables design through the production process and that the integration of design and materialisation is possible.

Subsequent to a decision on the visual effect during the design process of the Hangzhou stadiums , an optimization process was performed on the geometry in order to conform to a series of limitations driven by structural, modular, and programmatic parameters . The effective translation of the concept into a flexible parametric system that would enable growth and adaption for future design development and could take into account different geometric constraints was the main challenge of the optimization process. To solve this problem, the inner and outer limits of the geometry were defined in section using the original concept model as a starting point. Points were then mapped from the defined limits to serve as control points for B-spline curves. The curves were in turn utilised in defining the primary cross section. This method allowed the multiplication of the main truss along the elliptical forms. The petal surfaces were modelled as a sequence of developable surfaces connecting two adjacent petal rail profiles. Restricting the geometry to surfaces that could be developed was of paramount importance in considering the form petal shapes would assume when unrolled for manufacturing purposes (Shodek et. al. 2005). To attain the cross-bracing and lateral prop up center lines, a further subdivision of the curve geometry defining the trusses and petals was performed(Miller, 2009).

In the Kunthaus Graz project, computation allowed the design team realise the technical complexity which the building is characterised by , under tight budgetary constraints and deadlines. The important design solution was the structural support for the blobby skin, and the creation of material conditions that allowed the use of acrylic panels for the outer skin, which was driven by the robotic manufacture of the moulds used to create the Plexiglas sheets. The design is 'user friendly' because, integrated functions and the ability of some of the roof nozzles to change their orientation, tunes the level of illumination on the topmost floor to the specific needs of different art installation. In an urban context, design computation enabled the successful integration of an exciting form into the Old town of Graz (Cook et al., 2004)

5.1.2 Design Speed

In the design of Taipei Nangang Office Tower, the design was accelerated due to design approach and the parametric relationship between the programmes used. The ability of Revit to update changes in the geometry without the loss of previous information and produce the construction drawings was beneficial to the speed of the design.
Given that the design process of The Hangzhou stadiums followed a set of loosely defined symmetrical rules, it provided an opportunity for the speedy generation and evaluation of numerous iterations and variations from an aesthetic and proportional standpoint. The ability to use the same geometrical model for the generation of structural evaluation models also aided in speeding the design up.

More profound is the speed inherent in the designs of the Robotic walls and pavilion. All the processes were mediated by computation from design to fabrication. Apart from the initial load tests performed on the elements manufactured first in the Vineyard Gantenbein facade, there was requirement for further structural analysis as the test proved that reinforcements usually required for conventional prefabricated wall were not neccessary (Gramazio & Kohler,2006).

5.1.3 Creativity

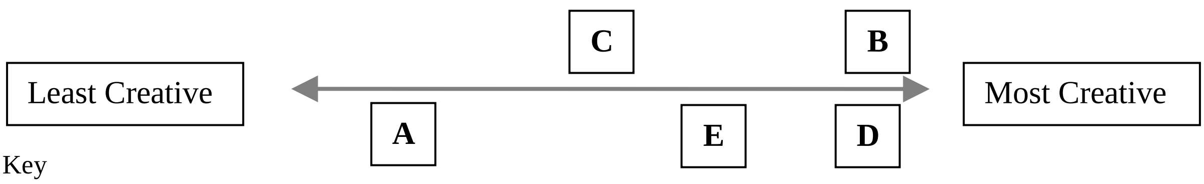
There was an urge after the study of various cases to argue that creativity has not been enhanced by computational tools as the initial ideas already exists and the only role played by computation was the realisation of the ideas. Oxman butresses this point by the statement of the fact that digital design is not revolutionary due to its new forms but because it proposes variations mediated by repetition(Oxman 2006).

This urge is immediately countered by the definition of the term enhancement. To enhance simply implies augmentation; improvement. Design computation is in no way impeding or taking over the designers' role as most traditionalist believe. Computational formal explorations do not eradicate human imagination but rather extend its potential

limitations(Terzidis,2003). Architects depended on hand sketches as a medium for the creative process and conceptualization, however in this technological age hand- made sketches and drawings have become insufficient means of communicating design ideas and the production instructions as seen in the cases studied especially in the design of the Taipei Nangang Office Tower by the Aedas Beijing group. Moreover, digital medium offers contemporary designers are presented the opportunity to easily and quickly form primary geometric shapes, similar to architects hand- constructed diagrams. The shapes, devoid of detail could also be considered preliminary because they provide basic conceptual information prior to design development (Smith,2005) as observed in the design of the Kunthaus Graz. The increased speed and capability of the computer to manipulate geometry infers an increase in the replication of creative impulses of hand sketches.
In reference to Liu's interview with Eisenman, Lynn and Mitchell, the design process of the Hangzhou stadiums is creative as' variations on the theme' were produced in ample time. The creation of the possible outcomes is attributable to the speed of the computer.

In all the projects, technology played a vital part in eliminating the barriers that could hinder the execution of design ideas. This role is most prominent in the Vineyard Gantenbein facade and the Research pavilion projects in which the construction techniques and details were a challenge. The Kunthuas Graz project was also innovative due to the discovery of techniques for fabricating the lean structural system, the joinery and the production process for the acrylic panels that eventually cover the double-curved geometry.

Below is a proposed creativity continuum, illustrating the degree of creativity across the studied cases.



Key
A = Taipei Nangang office tower
B= Robotic wall
C=Hangzhou stadiums
D=Research Pavilion
E= Kunthaus Graz

Fig 41: Illustrating the degree of creativity in the cases that were studied.

In summary, representation ,rationalization and adequate optimization of a non-Euclidean forms and algorithmic designs such as the ones evident in the studied cases was impossible by means of conventional plans, sections and elevations. The most realistic means of achieving them was as "a set of 3D data in a computer software package, later to be directly linked at the production stage, to cad-cam manufacturing tools"(Cook et al., 2004).

5.2 Limitations of the Study

Due to restrictions that arose from the time limit of this research, the technique of data collection was restructure to a desktop research project. This weakness prompted the rigorous study of additional cases to make up for the inability to collect primary data in form of semi structured interviews earlier proposed. The diversity in the sources of information retrieved however, has helped strengthen the validity of the research hypothesis.

Chapter 6

Conclusions & Recommendations

This thesis began with the assertion that design computation has been beneficial to architectural practice. The research claims of increased design creativity and solutions influenced by computation opposes the notion that computational design is just an avenue for the expression of radical or utopian ideas. After critical review of extant literature it was identified that the possibilities offered by computation were numerous. One of the commonly known advantages of digital-computational design is one generic to computation; the ability to process and store large amounts of data that the human brain tends to lose. This study has come to a conclusion that the benefits digital-computational designs include and are not limited to the following:

- Preservation of the designers' initial ideas
- Ease in form derivation through digital sketches and prototypes
- Ability to create various design themes in a limited amount of time
- Increased understanding of the production process
- Increased ease in communication between various members of the design team
- Ability to assess , evaluate and resolve conflicts of the design at early stages
- Ability to predict the future performance of a design

With a knowledge of these benefits, designers now have the time to focus more on the act of conceptualisation. However, a detailed understanding and fluency with the use of the computational tool(s) as this research identified determines the level of creativity of the designer engaged with it. Most tools tend to inhibit creativity of a designer who is not proficient with its use as the design process becomes a more pedagogical than helpful. At this point design computation could be characterized as redundant. The perceived complexity of the tool results in time loss.

On the creative side, contrary to the assumption that digital-computational designs are born of a need to create blobs, design solutions evident in the case studies are defining new uses for materials. "The ability for digital models to connect between design materialisation even at conceptual stages supports a new depth of contextualization and performative design"(Oxman, 2006). Architects are gradually taking back the control of the construction process as the constructability of projects is becoming increasingly dependent on the efficacy in communication between the design and construction information. The most profound impact identified is the elimination of the risk of redesigning as some architects resulted to during the pre-digital age. Evaluation of designs through digital means during the design process ensures that all construction details and processes are simulated and understood before actual construction. With the elimination of redesign risks also comes a reduction in overall project cost amongst other benefits.

Digital-computational design is also influencing new directions for the architectural design profession as architects are moving towards a future where there is no distinction between architects and digital architects or between traditional design processes and computational design methods. A future where designers are not "limited by the design process, but are designing the process".

Recommendations

This research identifies that the primary problem hindering the full acceptance of design computation apart from cost related matters and the availability of the technology is , that of oblivion. Most Architects in practice are still unaware or unconscious of the advantages and potentials of computational designs. Practicing architect should be sensitized on these benefits and training courses organised for those who are unfamiliar with computational methods. On the pedagogical level, this thesis proposes that all schools of design incorporate computational design courses into their curriculums to produce a creative calibre of designers. It is only after this reorientation that architects, would fully regain their position as 'master builders'.

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Appendix

Script I

```
' ---- R A S T E R   T O   M A T R I X --------------------------------
' -------------------------------------------------------------------
' ---- Converts a *.raw grayscale raster image into a matrix of numbers
' ---- representing the gray scale level of each pixel.
' -------------------------------------------------------------------
Sub RawToMatrix()

 ' ---- Asks for the input file ----
 inputFileName = Rhino.OpenFileName("Open", "Text Files (*.raw)|*.raw||")
 If IsNull(inputFileName) Then Exit Sub
 ' ---- Generates the output file name ----
 Rhino.print inputFileName
 file = Left(inputFileName, Len(inputFileName)-4)
 Rhino.print file
 outputFileName = file & "Data.txt"
 Rhino.print outputFileName

  ' ---- Asks for the image size (width and height) ----
 width  = Rhino.GetInteger("Width of the image in pixels ")
 height = Rhino.GetInteger("Height of the image in pixels ")

  ' ---- Opens the input file and assigns it to a handle 'fpInput' ----
 Set fsObjectInput = CreateObject("Scripting.FileSystemObject")
 Set fpInput = fsObjectInput.OpenTextFile(inputFileName, 1)

 ' ---- Opens the output file and assigns it to a handle 'fpOutput' ----
 Set fsObjectOutput = CreateObject("Scripting.FileSystemObject")
 Set fpOutput = fsObjectOutput.CreateTextFile(outputFileName,True)

 ' ---- For all the lines ----
 For i = 1 To height
  ' ---- For all the pixel in a line ----
  For j = 1 To width
   ' ---- Reads the ASCII coding of the gray level ----
   char = fpInput.Read(1)
   ' ---- Converts the ASCII coding to a 8 bit number (0 -> 255) ----
   gray = Asc(char)
```

```
      ' ---- Iteratively adds the current value to the line string ----
      fpOutput.Writeline(gray)
      'line = line & " " & gray
    Next
    ' ---- Sends the line to the Rhino shell ----
    'Rhino.print line
    ' ---- Prints the line on the output file ----
    'fpOutput.Writeline(line)
    ' ---- Clears the line ----
    'line = ""
  Next
  ' ---- Closes the files ----
  fpInput.close
  fpOutput.close

End Sub
' ---- Calls the sub ----
RawToMatrix
```

Script II

```
' ---------------------------- W A L L --------------------------------
' -------------------------------------------------------------------
' ---- Parametrically generates a brick wall
' -------------------------------------------------------------------
Sub Wall()
  brickWidth       = 25 '(10 Inc)
  brickHeight      = 12 '( 2 Inc)
  brickDepth       = 12 '( 6 Inc)

  mortarThickness  =  1 '( 3/8 Inc)

  wallHeight       =  20 'bricks
  wallWidth        =  40 'bricks

  wallBottom       =  0
  wallLeft         =  0

  ReDim gray(wallHeight*wallWidth)
  inputFileName = "c:\Panel40x20CData.txt"
  ' ---- Opens the input file and assigns it to a handle 'fpInput' ----
```

```
 Set fsObjectInput = CreateObject("Scripting.FileSystemObject")
 Set fpInput = fsObjectInput.OpenTextFile(inputFileName, 1)
 For i = 0 To wallHeight-1
   For j = 0 To wallWidth-1
     gray(i*wallWidth + j) = fpInput.Readline
     Rhino.print gray(i*wallWidth + j)
   Next
 Next
     ' ---- Closes the file ----
 fpInput.close

 Dim pt(7)
 sign = 1
 For i = 0 To wallHeight-1
   sign = -sign

   For j = 0 To wallWidth-1

     xj = (wallWidth-j)*(brickWidth + mortarThickness) + sign * (brickWidth+mortarThickness)/4
     zi = (i)*(brickHeight + mortarThickness)

     pt(0) = Array(xj,                  brickDepth, zi)
     pt(1) = Array(xj + brickWidth,      brickDepth, zi)
     pt(2) = Array(xj + brickWidth,               0, zi)
     pt(3) = Array(xj,                            0, zi)

     pt(4) = Array(xj,           brickDepth, zi + brickHeight)
     pt(5) = Array(xj + brickWidth,  brickDepth, zi + brickHeight)
     pt(6) = Array(xj + brickWidth,       0, zi + brickHeight)
     pt(7) = Array(xj,                    0, zi + brickHeight)

     brick = Rhino.AddBox (pt)
     center = Array ((pt(2)(0)+pt(0)(0))/2, pt(0)(1), (pt(2)(2)+pt(0)(2))/2)
     Rhino.RotateObject brick, center, (255-gray(i*wallWidth + j))*0.1
     'Rhino.addsphere center, 0.1* (255-gray(i*wallWidth + j))
   Next
 Next
 End Sub
' ---- Calls the sub ----
Wall
```