// {Machine Actuated Craft} //

By

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Figure001: Collection of models generated through the design experimentation process.
Throughout history the use of scale representations has been important in the process of creating architecture. In recent times the introduction of computer-aided design (CAD) has significantly altered traditional methods of conceptual design representation, mainly through a shift from the physical to the virtual.

The aim of the research is to explore the relationship between computer aided manufacturing (CAM) and the methods for extracting and producing qualities of a conceptual nature from computer and numerically controlled (CNC) machine, and how this could advance conceptual creativity formulating in buildable form.

The qualities that are inherently produced by CNC machining processes are then captured back into the three-dimensional environment (CAD), and then re-exported via CNC machining. The information that flows from the digital to the physical and then back again, creates new physical qualities that would not normally be produced, and allows for further investigation. Through the misrepresentation and reinterpretation of machine processes in this research, the output produces an object of an abstract nature created through identifying extraordinary expressions of tool paths. This 1:1 abstract object expresses qualities of craft produced by the CNC machine and creates a new form of craft that can be compared to the expression of the traditional craftsman and their trade. This simple movement between scales and formats begins to generate new design processes that in turn translate the conceptual expression of the object into a buildable form.

On final completion of the object this project has proven that CAM conceptual creativity can be translated and formulated into built form. A key observation of this research is that identifying CAM production techniques can produce abstract representation through a new means of design representation.
Relatives, friends and academic colleagues have been most supportive throughout my time at university. I have been fortunate to have been involved with a terrific group of fellow architectural students, and would like to acknowledge how much I have appreciated our discussions and having the opportunity to share ideas with such a willing collection of listeners. The Victoria University staff was most supportive, special thanks go to workshop technicians for their practical support, to Mathew Houston from the VUW disability support, the on going support from Lee Gibson, Linda Wong deserves a very special thank you, for her exceptional guidance she provided throughout my thesis work. My final appreciation goes to my family and in particular to my parents Bill and Bronwyn for their understanding and support and the personal sacrifices made to enable me to study fulltime. I look forward to life outside the university workshop and studio and reconnecting with my family and friends.
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Introduction

Throughout history creating scaled physical representations (models) of a conceptual design has had a significant influence in architectural and design processes and were regarded as being an expression of craft. The craftsmen who produced these scaled models were highly valued, however, it can be argued that this craft has been lost in the transition to modern technology where the introduction of computer-aided design (CAD) has altered the traditional methods of conceptual design representation. With the transition into CAD there has been a lack of investigation into the methods to retain fundamental techniques of visual representation, which has not been fully translated in the use of computer-aided manufacturing (CAM) and consequently has changed the manner in which architecture develops conceptual design creativity. Moon (2005) when discussing the use of models in the architectural process writes,

A new order of architectural representation, in the form of virtual three-dimensional renderings, computer modelling and walk-throughs and fly-bys, presents a challenge to the model’s traditional role. ...What this signifies for the future is unclear, but it prompts important questions. Is it possible that within a decade or so, the virtual will supersede the physical in the creation of architecture? (Para. 4)

The passion for model making was initiated in the early stages of my degree and throughout my architectural studies I have used models as design processes when developing conceptual ideas. It was a natural progression to use my Masters thesis as a way of expanding my knowledge of the model and exploring its contemporary function in 21st century architecture design and practice. Therefore this thesis explores the significance of physical object modelling through the process of investigating modern expressions of conceptual design ideas using CAM in conjunction with CAD. This raises the research question; what is the potential of
utilising CAM technology for conceptual creativity formulating to a buildable form?

The scope of the research is defined by the following aims and objectives. The research aim is to explore the relationship between CAM and the methods of extracting and producing objects of a conceptual nature through computer and numerically controlled machines (CNC Router) manufacturing techniques and how this could advance conceptual creativity formulating in buildable form. The research objectives are to explore: if what constitutes craft is present in the application of modern computer-aided manufacturing; if these physical objects reveal unforeseen qualities not predicted by the geometry created in the three-dimensional environment; if the qualities produced by the CNC Router can be used as a practical conceptual design tool; and if the abstract expression produced by the CNC Router can be formulated into a buildable form.

Current architectural theory and knowledge provides a foundation for the research. The ideas of several theoretical and experimental architects were drawn on. These include Mitchell’s (1977) discussion on generative systems. And Kalay (2004) who refers to design processes being intertwined by four phases: feasibility analysis; solution synthesis; evaluation; and communication. With reference to experimental architecture the ideas of Fiel (as cited in Beauce & Cache, 2007) who refers to ‘architectonic practice’ and Beauce & Cache (2007) who regard their work as being ‘non-standard architecture’ are drawn on. Also called on was Guthrie’s (2005) ‘system of logic’ applied to construction processes specific to form and material.

The research has been undertaken based on the context that it focuses on a process to generate conceptual design creativity that could be used within architectural practice rather than with the aim of the design outcome being a resolved architectural building. The research expands on how CAM is used as a tool when creating design opportunities. The process designed by the researcher is significant in creating conceptual design ideas as it is applied at the early stages of design creativity. With this aim achieved the research will provide the foundations to create applications to further lead into the experimentation of the buildable form.
Methodology

The method chosen to conduct the research was physical practical experimentation. The method used technical experimentation processes undertaken on CAM systems working in conjunction with CAD to identify machine production processes within physical model/object making. To undertake the experimentation process the tool selected by the designer was a 2.5 axis CNC Router. The production of physical objects was a key design feature undertaken throughout the research.

The research method involved undertaking three separate experiments. Experiment 001 explored if craft is present in the application of modern CAM. The experiment also investigated the significance of scale when information flows from digital to the physical and back again. Experiment 002 explored a CAM method of subtraction revealing aesthetic qualities of an abstract nature utilising the CNC Router. It also investigated if the CNC Router can be used as an architectural conceptual design tool.

Experiment 003 explored how conceptual qualities produced by the CNC Router can be used as an architectural thinking mechanism and how this can be formulated into a buildable form and how, by the use of both CAD and CAM, the designer could formulate a design outcome of the buildable form at a new 1:1 scale.

The CAM architectural design tools varied across the three experiments. Experiment 001 utilised CAD production techniques, the CNC Router and a physical 3D scanner. Experiment 002 utilised CAD production techniques, CAD CNC software and the physical set parameters of the CNC Router. Experiment 003 used CAD systems as the main production tool and utilised a physical 3D scanner, CAD coded software, CAD production technology and 4.5 axis CNC Router.

The processes followed in the three experiments are set out in figure: 002.
Figure002: Stages of Experimentation Processes for Experiment 001-003

**EXPERIMENT_001**
- Computer Generated Site Model
- Comparison of the Physical to the Digital
- Evaluation of the Physical Scale to the Digital
- Physical Model 3D Scanned into Digital Environment
- Production of 1:2000 Physical Site Model

**EXPERIMENT_002**
- Components of 1:2000 Site Model Extracted from CAD Geometry
- Identifying CNC Router Aesthetic Surface Quality
- Identifying Generative System within Set Parameters of the CNC Router
- Aesthetic Surface Qualities Produced by Misrepresentation Process
- Abstract Object Created by CNC Router
- Physical Generative System

**EXPERIMENT_003**
- Reinterpreting the Object within the Digital Environment
- Physical Aesthetic Quality Generated within the Set Coded Software
- Allocation of New Given Stock Material
- Assembly Architectural Detailing System
- Reintroducing CNC Router Tooling into the Buildable Form
- Reintroducing CNC Router Tooling into the Buildable Form
Data Recording

Multiple sources of data were generated throughout the experimentation process. Due to the substantial volume and diversity of this data it has been collated as a separate appendix to accompany the thesis.

The data has been archived as follows:

- Computer screen captures were used to record the CAD system processes and then formatted as jpeg images.
- The CNC software material construction data has been recorded in chart format.
- Computer screen captures were used to record the CNC software print preview of the three-dimensional geometry before output to the CNC Router.
- The generative code (G-code) produced by the CNC software has been recorded and converted as a Word document.
- A visual video documentation record of selected processes, including the assembly process of the buildable form, is recorded on a CD disk.
- A photographic record is held of all physical components produced throughout the experiments.
- Two-dimensional CAD working drawings of the construction process to assemble the buildable form has been documented.

Explanation of Terminology used by the Researcher

Terminology has been used which has specific meaning in the context of the experimentation and the design outcome processes. The researcher’s definitions of these terms are:

Boundary of resistance: is the level to which the CNC Router can perform within its set parameters.

Boundary of scale: is the difference between aesthetic qualities of each scaled model in relation to the different material use.

Object modelling: is when the designer engages with physical materiality to formulate a conceptual design idea to be translated to the built form.

Physical generative system: is applying multiple variables to fixed parameters
producing unforseen results as physical objects.

Physical representation: is the physical presence of conceptual design idea represented as a product of the 1:1 at a given scale.

Point of detachment: is when the designer is detached from construction process of the physical model.

Stock material: is material applied at any given size to CNC Router to construct the physical model.

Thinking mechanism: is the ability of the designer to draw inspiration from a given object to be formulated into a buildable form.

Unforseen aesthetic quality: is an attribute revealed by the CNC Router during the manufacturing process.

Variables: multiple geometries extracted from the 1:2000 site model that were applied to the CNC Router.
//{Chapter Two}//

Review of Literature

In chapter two the review of literature provides a conceptual framework and foundation for the research. The review discusses the historical concept of craft and its varying definitions and how the notion of craft has become detached from modern architectural practices. As physical models are a key aspect of the research methodology of practical physical experimentation the use of models in historical and current architecture is also reviewed. The architectural technologies used in the research, CAD and CAM their production techniques, and the linkage they have with the notion of craft in modern architecture is reviewed. Building on the review of literature, chapter three is a review of practice discussing the theoretical knowledge underpinning the research and its association with the research design processes in current architecture.

Craft and the Craftsman

Defining the expression craft has generated much discussion and debate. Risatti (2007) views it necessary to explain what is referred to by the term craft because of confusion surrounding its definition. When discussing the theory of craft Risatti (2007) refers to craft as being specific objects and the profession concerned with the creation of these objects. He identifies the skilled activities, with which and through which, the objects are made as craftsmanship. He gives these definitions to separate craft objects from the skills utilized to make the objects, while at the same time emphasizing the connection between craft and the skilled hand intrinsic to craftsmanship.

Robertson (1961) views craft as a fundamental human activity involving the skilled labour of materials. He sees craftsmanship as, “…the whole body involved in an expressive rhythm relating mind and material for a specific purpose” (p. 27). Robertson acknowledges that the craftsman has evolved tools and that the professional craftsman emphasizes his tools. Collingwood (as cited in Robertson, 1961)
writes, “The craftsman’s skill is his knowledge of the means necessary to a given end.” However Robertson (1961) differs from Collingwood and believes, “The craftsman should be concerned with the end, the product and its effect on the lives of others not only with the means necessary to achieving it.” (p. 28). He sees craftsmanship in its purest form, as a craftsman generating the object from its inception to its finished form and in so doing conscientiously controlling the work at every stage, the nature of the raw material and the traditions of its use.

Before the Industrial Revolution the skilled hand always carried out the production (Risatti, 2007). The words craft and craftsmanship referred to the quality of the making and assumed the skilled hand was the source of this quality. This is no longer the case in our modern world as the skilled hand is not the sole producer of objects. Today when the terms craft and craftsmanship are used they often have a somewhat different, less precise meaning than in historical times. Today craft and craftsmanship often refers to things made by machines and those made by the skilled hand differ because different conceptual attitudes are involved in the process. Therefore in today’s world skilled activities of the hand alone are not sufficient to define something as a craft object (Risatti, 2007).

For Risatti (2007) the traditional production of craft objects along with the dialogue that has surrounded them has been focused on practical matters. He sees materials, tools and techniques as having dominated craft discussion in contrast to abstract theoretical models or artistic/aesthetic issues. Risatti (2007) believes concern with material is important to craft and the field of craft is categorized and identified by it. Craft and categorisation according to material, working methods, and techniques reflect a long heritage and is viewed as being founded in the medieval guild system (McCullough, 1996; Risatti, 2007). This practice continues today in the form of professional bodies operating under a recognised professional code of practice. The survival of this legacy acknowledges the significance of materials, technical skills and technical knowledge needed in the field of craft. As Risatti (2007) states, “To draw or paint an image that resembles a bowl is a very different
enterprise from making an actual bowl” (p. 16).

Risatti (2007) considers that complexity in terminology as well as the origin of the word craft reflects the real need of craft specialists to focus on the mastery of specific materials and techniques. He believes this makes the existence of a shared framework between crafts difficult to distinguish and understand. In his view it also undermines the possibility of a cohesive perception of craft and the reality of any mutual theoretical ground, which is necessary for critical understanding. However he believes these differences disappear when craft is considered from a point of view of function. Risatti (2007) states,

*When this is done the relationship between material, technique and form becomes clear and meaningful, because practical physical function, what in the past would have been called “applied function,” is that element that has been common to crafts objects for millennia, regardless for the material or process of their making. (pp. 17-18)*

Therefore it is practical physical function that fuses what otherwise would be separate areas of activity. Risatti (2007) chooses the term practical physical function to emphasise the intellectual as opposed to the manual. He believes the notion of practical physical function helps with the examination of the subtle but complex relationship that exists in craft. For Risatti (2007) the value of practical function is that it can help understand unique features of both traditional and contemporary craft.

Diderot’s encyclopedia (1751-80) (as cited in McCullough 1996) states, “Craft. This name is given to any profession that requires the use of the hands, and is limited to a certain number of mechanical operations to produce the same piece of work, made over and over again.” (p. 12). McCullough (1996) applies this definition to the modern definition to the processes used by a skilled computer graphics artisan.

*His or her hands as preforming a sophisticated and unprecedented set of actions. These notions are quick, small, and repetitive, as in much traditional handwork, but somehow they differ. For one thing, they are*
faster - in fact, their rates matter quite a bit. They do not rely on pressure so much as position, velocity, or accelerations. The artisan’s eye is not on the hand but elsewhere, on a screen. The actions have a practical component, and the skill may be practiced for a livelihood and trade identity (pp. 19-20).

McCullough (1996) believes craft must be looked at closely and as part of developing more appealing technology there must be an understanding of what matters in traditional notions of practical form-giving work. He believes this will take, “some study of tools, some study of human-computer interaction, and some study of practicing the digital medium.” (p. 19). In digital production McCullough (1996) refers to craft as: where the designer applies standard coded software to apply variables to set parameters within the coded software to produce multiple unforeseen results. He sees computer geometric modelling as crafted when the designer employs limited pre-packaged software capacities inventively and creatively.

McCullough (1996) upholds that craft remains skilled work applied toward a practical end. It is a consistently skilled practice using particular tools, materials, or media for the purpose of making increasingly well-executed objects. He describes craft as the application of personal knowledge to the giving of form and is the condition in which the intrinsic qualities and economies of the media are promoted to shape both process and products. McCullough (1996) sees craft remains about the newly practical and individually prepared object due to digital computing.

Piano (as cited in Schodek et al., 2005) believes it is important to develop an understanding of the craft of architecture before integrating computer-aided technologies into the development of a building. He states, “the modern meaning of craftsmanship lies in the production stage preceding the industrial stage: the prototype.” (p. 35). Piano (as cited in Schodek et al.,) cautioned that CAD can be superficial and the design can be insufficiently resolved when it is studied only in its graphic form. He believes it is preferable to work with a physical model whenever possible, particularly when a
design is unresolved. Schodek et al. (2005) believes that because CAM facilitates the translation of the digital model into three-dimensional physical models, it can be applied to Piano’s design philosophy by expanding upon the traditional handcrafted modelling method through CAM producing machined models.
The Physical Model

Throughout history models have influenced architecture and its processes, and an understanding of how models are used remains important to the study of architectural design. Smith (2004) sees the architectural scale model as a thinking and defining mechanism for understanding and demonstrating architectural concepts. He believes models allow architects to test the potential building; to explore and define the unidentified; and to develop unexpected conclusions. Smith (2004) also stresses the importance of understanding how models are used in the design process because both their potential for meaning and their technique can be seen as representative of the architects’ thinking.

Models are one of the tools architecture uses to visualise and communicate architects’ ideas. Of all the approaches used in architectural representation the model is the only physical three-dimensional realisation of an architect’s idea and when taken to completion it becomes a three-dimensional thing (Moon, 2005). Moon (2005) states, “However much time we might spend looking at two-dimensional (2D) images, we live in a 3D world” (p, 11). Moon (2005) outlines the advantages of the model as: it is closer to reality than other architectural visual representation; the eye understands the model more easily; it is more accessible to a wider range of people; it can be more readily understood than computer images; and it requires less training to read than an architect’s drawings. Pran (as cited in Moon, 2005) describes the model as, “a kind of universal language. Everybody can understand a model; that’s the beauty of it. Freehand renderings and three-dimensional computer renderings have a great appeal, but models speak to us all” (P.11). Moon (2005) believes by having the option to use CAM alongside simple and complex hand techniques keeps the medium healthy. Daniel Libeskind (as cited in Moon, 2005) compares the relationship between the architect and the model to that of the puppet and the puppeteer. The energy between them makes the model come alive. But when the model is removed from the hands of the maker the strings are cut.
Computer-Aided Design

The introduction of computer applications in the 1960’s saw the beginning of a transformation in architectural design and design processes (Schodek et al., 2005). CAD has provided a new design development framework for enhancing the ability to manage complex geometries with better precision, enabling faster execution of the design process. Computer-aided applications assists in the explorations of iterate design differences and they provide a greater understanding of the consequences of the materials and methods. Also full-scale mock-ups of building components allows a means to validating and evaluating the attributes of a design as well as simulating the fabrication process and final production (Schodek et al., 2005).

When investigating from a theoretical perspective the history and development of computer-aided design Mitchell (1977) suggests the use of a generative system as a architectural design framework. He explains that generative systems over time have had a long and varied history including being used in the growth of engineering and architectural design methodology. To support his case Mitchell (1977) uses Leonardo da Vinci’s discovery of a basic schema that da Vinci used in developing a complete series of related central-plan churches. Mitchell (1977) explains that classical and formalised architectural design methods of the 19th century were based upon systematic investigation of different ways in which various elements from a fixed language could come together in different combinations to generate architectural forms. He believes a design system that forms combinations of standard elements from which design concepts are generated is still relevant in today’s architectural practice. Mitchell (1977) expresses that generally a generative system does not directly create the actual object sought but instead it creates a representation model or design for the object that can be translated into the physical form. He sees the development of representation models or designs as quicker, more straightforward and less expensive to manipulate than the real object. In so doing it gives the designer unique insights into design issues and considerably help the process of generating a design outcome.
Figure 003: Gehry’s Walt Disney Concert Hall
On ancient building sites the architect worked on the site and relied upon a combination of demonstrations and spoken instructions. With basic design representations comprising of templates, rough sketches, and physical models to express their design intentions they would convey these to the workers who were responsible for constructing the design. The introduction of parchment and paper saw geometric construction procedures and technical drafting instruments challenge these traditional ways. Design ideas were now explored on paper and discussions and presentations were organised around drawings and scale models. The outcome was that design processes became a comprehensive detailed set of construction documents (Kalay, 2004).

Digital technology saw the idea emerge of replacing paper drawings as primary representations of designs with digital representations stored in computer memory and manipulated by means of interactive computer graphic interface. The potential for digital storage and computation capabilities was recognised and this was the beginning of CAD systems being introduced to architectural practice. Although CAD technology made design work more efficient, it was argued CAD had not opened up new areas to the architectural imagination. This changed when several architects produced work that would have been impossible without innovative use of advanced information technology. An example is Frank Gehry’s Walt Disney Concert Hall in Los Angeles California, which, is viewed as depending directly upon perceptive use of three-dimensional modelling (Kalay, 2004). Kalay (2004) believes the progression of CAD in architecture is the investigation of the most suitable role that technology can play in the architectural design process.
Figure 004: Schodek et al (2005) Boat Hull Translation
Schodek et al. (2005) explains the difficulties in defining and representing curves and complex shaped surfaces in a solid modelling system. Many objects have very complex geometries, for example the hull of a boat. Schodek et al., (2005) point out that it is not easy to precisely describe the hull of a boat by a series of two-dimensional drawings leaving much to chance or to the boat builder’s interpretation. Schodek et al. (2005) believes the lack of exact numerical definition of the final surface shape might not pose a problem to the practised craftsman who is skilled in building boat hulls and uses their craft knowledge to create the exact shape of the hull. But attempting to make the same hull in an automated machine environment poses a totally different problem, as machines must be told precisely what to do. Therefore the designer needs to accurately specify the complex shape of the hull in a numerically based language that the machine control system can understand. Providing the capability to precisely numerically model highly complex curves, and consequently for related complex surfaces, has been a motivating force in developing more sophisticated computer modelling systems (Schodek et al. 2005).

For Kalay (2004) the ability to convey information visually has been the architect’s primary means of communication and representation. In his view the introduction of computers into architecture has added to enhancing realism through developments in computer graphics. He points out that computing technology presents much more than better productivity over existing means of communication and representation. He suggests the possibility of changing communication and representation in architecture with the aid of computing technology is grounded in six properties of computers. Kalay (2004) sees visualisation as one of these properties. He sees that computer technology has enabled the designer to produce photo-realistic images of yet imaginary artifacts and environments. Kalay (2004) sees visualisation is part of the larger realm of computer graphics and in the context of CAD refers to the process of converting the data structures that make up the geometric model of an object into a graphical form that can be shown on the screen of a computer or printed on paper. He points out visualisation is important as a form of communication in architecture, as much of human ideation and perception of externally generated information is eye-
related. He states, “Vision more than any other sense dominates the art of architecture” (p. 162). Kalay goes on to explain that the architect is trained to understand visual information including visualisations that are incomplete and imperfect. He declares that the architect can see three-dimensional volumes illustrated by two-dimensional drawings; understand curvatures; and discriminate small variations in shading. Because of this he sees advances in CAD have been closely linked to advances in visualisation. Therefore computer-aided visualisation had to arrive at a moderately advanced level of development before it became an acceptable architectural tool (Kalay, 2004).
Computer-Aided Manufacturing

According to Pottmann et al. (2007) architectural models are an important part of architectural design projects as they have a role in the development of a design and in the representation of the finished design at different scales. He considers that digital fabrication and digital manufacturing are used in close relationship to digital modelling techniques and are used in the manufacturing of a finished object at full scale. Pottmann et al. (2007) believe there is a need when discussing model making to discuss scale as he sees the scale of a model as what stimulates the level of abstraction of a model through to 1:1 implementation. Also the same design geometry can support the development of mock-ups at all scales. Model building is starting to be governed by digitally created components and full-scale designs are increasingly relying on digital fabrication for complicated geometries. It is seen that digital fabrication processes have blurred the distinction between models and the full-scale building as the same information used in model making may be used for fabricating the final building (Pottmann et al., 2007).

Pottmann et al. (2007) views from an architectural design perspective that the fabrication technique and the choice of stock material play a critical part in the design process and in the aesthetics of the final object. Also the selection of a fabrication technique can lead to a specific aesthetic due to the geometric translation necessary to produce its parts and as a consequence the geometric translation can influence further design development. Pottmann et al. (2007) points out that the translation of a design idea into fabrication processes can be complex. The choice of the fabrication process also affects the representation of the design and this could require a slightly different procedure of abstraction of the core design idea. It creates specific challenges to the understanding of geometry, as the outcomes must be valid for the production of a rendered representation and vigorous enough to obtain fabrication information from it that allows the geometry to be built using CNC machines (Pottmann et al. 2007).
Figure 005 The Phare Tower project in Paris is used by Pottmann et al. (2007)
Computer-Aided Manufacturing Techniques

Three-dimensional printing

Three-dimensional printed models produced over different scales can be used as design outcomes at all steps of the design process in architectural practice (Pottmann et al., 2007). The Phare Tower project in Paris is used by Pottmann et al. (2007) as an example of using three-dimensional printing in the design process, both for representational models and for design development. Three-dimensional printers have the precision and intricacy of detail for illustrating architectural representation models. However for a small-scale model to be printable, the geometry has to be altered and thickened to fit the machine printing constraints (Pottmann et al., 2007).

Machine modelling

Subtractive techniques create geometric models by the extraction of material from a solid block or sheet. Layers of material are removed until the target surface is reached. However it is likely a model will not be machined out of a single block of material if it is large or is made up of complex geometry. In situations such as this the decomposition of a model into machineable parts is a crucial step and is carried out in parallel with the machine and tool selection. In small models some interior surfaces are simply not reachable without collision of the tool with the outer lying parts (Pottmann et al., 2007). With a 2.5 axis router, undercuts are not possible and therefore the model has to be divided into surfaces that can be reached from above without model interference and surfaces that have to be milled from the opposite side. Even with routers with five axis not all surfaces may be accessible due to the need to hold the stock material (Pottmann et al., 2007).
Figure006: Greg Lynn Coffee Alessi Coffee and Tea Towers
Computer numerically controlled (CNC) machines

The CNC Router is an automatic operating system controlled by data generated by computer software. The advantage of CNC machining is the operating system doesn’t require any form of manual operator to control the machine in the cutting process. The cutting operation is referred to as a notion. The CNC Router movements are driven by a stream of sentences outputted by CNC software in the form of a generative code (G-Code). The co-ordinates the G-Code follows removes the material to expose the shape generated by the CNC software. The CNC software translates the three-dimensional object into a form of commands, which in turn are then sent to the CNC Router (Lynch 1992). CNC Routers, range in sizes and number of axis. Routers with low axis count use cutting-beds as the support to hold the cutting stock materials. The tool head is loaded with a fast-spinning router tool used for carving material when moved laterally. Router end bits are used when cutting parts in more than two dimensions. Routers with more than 2.5 axis are complicated mechanically, and the degrees of freedom increase the complexity of tool path generation. Five-axis and higher number mills exist and very large-scale mills are used in the automotive industry for milling full-size foam mock-ups for concept cars. These mills use soft milling foams that require less force allowing the mills to be scaled up more easily (Pottmann et al., 2007).

The constraints of the machine limit the possible operations and an example of this is a tool following a milling tool path to construct the surface of the object. With respect to the geometry there are limited degrees of freedom when adjusting the milling tool. As the machining progresses the situation constantly changes due to the removal of material. The tool path influences the possible surface qualities and cutting times. In relation to architecture the wider use of machine tooling techniques has raised awareness of the aesthetic choices involved in CNC manufacturing. An example of this is Greg Lynn utilising the cutting marks left behind on foam plugs used for forming the titanium sheet metal of his Coffee and Tea towers as an aesthetic feature of the creation process (Pottmann et al., 2007).
The literature review has discussed the relationships between craft and the craftsman and how the association has developed overtime. The debate over the terminology of craft has not been resolved, as we have moved into modern times with the introduction of CAD and CAM technology. This research will go on to explore the relationships of craft and the craftsman in a modern context of architecture through practical experimentation utilising CAD and CAM technologies. The findings from the experimentation process will then be discussed in the context with the theory, which has been set out in this literature review.
Review of Practice

A requirement of this thesis is to identify the link between the research question and the design process undertaken in the research and how this relates to the practice of architecture. This chapter will survey current architectural practice and precedents relevant to the research. Qualifications, gaps and weaknesses in current practice and the relationship of the research to current practice will also be briefly discussed.

Architectural Precedents and Qualifications Used to Influence the Research

In exploring precedents of architecture in relation to the research, the researcher looked to the concept of ‘best practices’ to achieve a good design solution. Kalay (2004) believes ‘best practices’ can be achieved through encouraging architects and researchers to continue to develop architectural theories, methods and tools. He sees the benefit of ‘best practices’ to architectural practice occurring when architectural design becomes more foreseeable and opens the way for critical analysis and improvement.

The process of architectural design has been practiced over centuries however it was not formalised into architectural theory until the 1960’s (Kalay 2004). Design processes make certain the architect’s creations meet the design goals, tolerate the design constraints, and reduce the likelihood of errors. According to Archea (as cited in Kalay, 2004) architects regard design as a “search for the most appropriate effects that can be attained in a unique context” (p. xiii) and
Rittel (as cited in Kalay, 2004) views this search as being “an activity aimed at achieving certain desired goals without undesired side- and after-effects” (p. xiii).

Design processes are a precedent of architectural design and are an important factor of in this research. The researcher has used Archea and Rittel’s (as cited in Kalay, 2004) theoretical views of design and design processes to support the research methodology that assists in answering the research question. The three experiments explored these precedents by: revealing aesthetic qualities created through CNC Router manufacturing techniques; testing materiality; using CAD geometry to generate multiple unforeseen physical scaled objects. This resulted with the desired goal of achieving the buildable form bringing a physical 1:1 outcome to the design processes.

The solution synthesis is the imaginative phase of the design process. The designer forms ideas and possible solutions that might address the goals, constraints and opportunities recognized during the feasibility analysis phase. This is an instinctive process by the designer in finding an understanding of form, materials and the course of the project. The designer’s instincts came through in the experiments when deciding on factors such as the scaled representation of physical object modelling and variations in material selected by the designer.

The design process is intertwined by four phases: feasibility (problem) analysis; solution syntheses; evaluation; and communication (Kalay, 2004). The feasibility analysis is the phase of the process when the designer seeks to identify the requirements of the project. This involves: identifying the goals to be realized; the constraints the design will need to abide by; and the possible side effects and after-effects design solutions might generate. Feasibility analysis applies in experiment 001, with a key factor being the designer’s understanding of the tool (CNC Router) and its manufacturing capabilities and restraints in relation to the CAD geometry applied. The goals for each stage of the experiment were set and side and after-effects were progressively resolved by the designer’s thinking mechanism before progressing through the stages of the experiments.
The evaluation phase compares the recommended solution to the goals, constraints, and opportunities developed in the synthesis analysis phase of the design process, to recognize compatibilities and conflicts and establish the degree to which the proposed solution achieves the requirements of the project. Outcomes from the evaluation phase are communicated back to the previous phases for further development of the solution or for changing the requirements. Evaluation is a factor of the design processes in experiments 001 and 003 involving moving back and forth between the digital and the physical to achieve solutions when CAD and CAM restraints were identified.

The communication phase helps the designer record his or her own thoughts to stimulate thinking leading to further development of the solution. It also allows participants in the design process to become informed of the evolving goals and solutions (Kalay, 2004). Kalay describes communication as “… the glue that connects the different parts of the design process to one another and serves as its record and its stimulus”. (p. 13). In the experiments this relates to the design processes of substraction utilising the physical abstract object as a thinking mechanism to lead to the construction drawings to formulate the final physical buildable form. The construction drawings connect the final digital and physical and serve as an archive to the design process.

In everyday architectural practice scaled models have continuously been a preferred method of communication as they demonstrate buildings in a three-dimensional mode. They have also allowed architects to experiment with different design solutions and test them for form and function before committing a design project to a built form (Kalay, 2004). For Smith (2004) scale models can assist with eradicating problems in perceiving the future building, as they can be less ambiguous than drawings. In the research the designer created a database of physical models to inform the creativity process. This enhanced the visualisation process giving a three-dimensional perspective when evaluating possible design solutions.

There is a long history between model building and architectural practice and architects have used scaled models as a way of giving an overall perspective of a design
at different scales (Pottmann, 2007). Representation models are usually built at small scales but a consequence of this is that it reduces the amount of detail that can be shown. Therefore abstraction of detail and material has a key role within architectural model building (Pottmann, 2007). Pottmann et al. (2007) states, “The choice of abstraction is informed by the most important aspect to be represented in the model.” (p.573). He also states that the geometric properties of materials can be more important in the context of geometric model building than the realistic appearance. He suggests, “Materials used in models may also be chosen more for what they represent conceptually than as a representation of the final material choice” (p.573). The properties of the modelling material used in experiment 002 to create the abstract objects furthered the design aesthetic quality at the required scale. However this material was not suitable for the construction material of the final built form where a more standardise material could add further aesthetic value.

It could be argued that there is a technological operational precedent current within architectural practice and Fiel (as cited in Beauce & Cache, 2007) refers to this as architectonic practice and regards this as developing a new generation of experimental architects who aim to open new regions of discussion. Objectile, founded by Beauce & Cache is an architectural organisation that has fully adopted CAD and CAM systems. Beauce & Cache (2007) have termed their work as ‘non-standard architecture’ which they consider cuts across artistic, industrial and digital disciplines. They regard the architectural project as consisting of a model and that each project is a modelling of the basic sketch for creating the co-ordinate instructions (G-code) that drive the manufacturing processes of computer numerical controlled machines. Beauce & Cache (2007) use a process of generating fabricated objects produced through CAD and CAM. The objects are examples of variations to the project that can be used to verify technical issues. They see this process as the work steps prior to the fabrication of the final outcome. The designer has utilised the G-code system but the point of difference in the research is the development by the designer of a physical generative design system to create variations of abstract objects as possible design processes before engaging with the buildable form.
A qualification for undertaking this research was informed by Guthrie’s Cube project. Guthrie’s (2005) project aim was to learn how to develop a language within a construction process that keeps an essential relationship between form and material. Guthrie (2005) views the teaching of architecture as working with abstractions, which are characterised by drawings and models that are usually not realised. He views abstractions as useful as tools but they have limitations that are essential to architecture. Guthrie (2005) believes abstractions are limited in the realm of scale and materiality, as they do not identify the spatial and behavioural properties of the materials they represent or identify the physical outcomes of the designer’s decisions. Guthrie (2005) suggests that applying a system of logic that maintains a meaningful relationship between form and material can close the gap. Also a system of logic allows for a “…coming to terms with the material’s physical reality” (para. 3). This is revealed through a repetitive give and take exchange that connects the hands, the materials, and the imagination in a feedback loop, which in turn forms a set of rules that join the part and the whole. Guthrie (2005) advocates for conceptual processes to be kept open-ended because predetermined ideas can always change when they meet the physical reality. He tries to make design inseparable from the act of making. Guthrie’s (2005) system of logic influenced the design processes for experiment 003. The thinking mechanism (language) applied to the fabrication techniques informed the essential relationship between the digital design process (form) and the physical construction of the buildable form (material).
Gaps and Weaknesses Identified Relevant to the Research

Within the world of design changes are occurring rapidly due to CAD and CAM technologies, which are having a beneficial effect on the work of many designers (Schodek, 2005). However Schodek (2005) argues that in architecture an understanding of these technological capabilities is underdeveloped. He acknowledges a few designers within architecture have embraced the use of CAD and CAM techniques but sees the field, as a whole has been slow to adopt these techniques into everyday architectural practice. Schodek (2005) believes this is due to CAD and CAM technologies not being well understood. He explains that although designers are skilled in CAD techniques they often find it difficult to understand the connection to the world of CNC machines and the interrelated manufacturing processes. Schodek (2005) expresses a confidence that design systems can be further developed and that these systems can be made with a quality and accuracy that in the past has been difficult to achieve. He also believes inherent in these technologies are ideas “…for interactions among design, analysis, and production activities that both challenge current approaches and provide positive alternative approaches for the future” (p. ix).

Lynn has led the way in defining how architects use advanced digital technologies as a design tool (Rappolt 2008). Lynn suggests (as cited in Rappolt, 2008) that there is a need within architectural practices to buy CAM tools and learn how to “talk” directly to these tools that are used to manufacture the components that make up their buildings.

The gap identified by Schodek and Lynn between designers’ CAD skills and their lesser understanding and use of CNC machines is a focus of the research. The researcher has sought to contribute towards the closing of this gap through increased knowledge of the CNC Router and detailing this through a physical practical experimentation process. As technology has evolved CAD and CAM have still been regarded as two separate technologies within architecture. The researcher has endeavoured to add further knowledge through establishing an inter-relationship between
CAD and CAM at the early stage of conceptual physical object modelling.

Criteria Applied to Interpret and Evaluate the Design Process

The research has been undertaken based on the context that it focuses on a process to generate conceptual design creativity that could be used within architectural practice. It is not the aim of the research that the design outcome is a resolved architectural building. This is an important distinction, as the latter would require significantly expanding the research scope.

The thesis has an emphasis on design processes through physical practical experimentation. Documentation of the three experiments has been through text supported by images, charts and figures. The supporting data for the experiments is substantial and much of this is recorded in the appendixes for in-depth understanding of the experimentation and construction processes.
Figure 007: Experimentation Processes for Experiment 001

EXPERIMENT_001

Computer Generated Site Model

Comparison of the Physical to the Digital

Evaluation of the Physical Scale to the Digital

Physical Model 3D Scanned into Digital Environment

Production of 1:2000 Physical Site Model
Physical Practical Experimentation

This chapter sets out the experiments undertaken for the research. The supporting images, tables and charts are to be read in conjunction with the text. The underlying data of the design and construction processes is provided in the accompanying appendices.

Computer Numerically Controlled Inspired Design

Introduction

This experiment explored the first research objective; if what constitutes craft is present in the application of modern CAM. The experiment also investigated the significance of scale when information flows from digital to the physical and back again. With this achieved the designer gained an understanding of how the CNC Router can be utilised in architectural practice when making physical models when addressing site and context. Figure 007 is a visual representation of the stages of the first experiment.
This image displays the CAD coded software used to create the digital site model and the geometry of the translation of the traditional physical model making techniques.
Computer Generated Site Model

Traditionally architectural models would be produced by hand. Traditional techniques used in making physical architectural site models are: volume massing for existing buildings; layered topography at scaled intervals; layout of transportation (primary and secondary); and boundary edges. In experiment 001 the designer developed a process that varied from traditional physical architectural model making techniques. This new process used CAD construction to create a three-dimensional model of the site location. The traditional process was adapted to a three-dimensional coded modelling software programme (Solidworks)\(^1\), which complied with the set parameters of the coded software of the CAD programme required to make the three-dimensional site model.

Refer to illustration that explains the translation of modelling using CAD coded software.

\(^1\) Solidworks is a CAD software programme with set coded parameters that assists in generating three-dimensional models in a digital environment.
This image displays the physical site models produced by the CNC Router displaying materials and the range of scales used.
Comparison of the Physical to the Digital

The geometry created in CAD was input into the CNC Router software\(^2\) and output through a 2.5 axis CNC Router producing a physical model. This point in the process when the machine constructed the physical model can be viewed as a point of detachment. Three different materials were used to produce the machine generated physical models: Ciba-Tool; Medium-Density-Fibre-Board (MDF); and Plaster of Paris. The three materials were tested over four different scales: 1:10000; 1:10500; 1:11000; and 1:15000. This allowed for a visual analysis of the significance of scale and material on the machine generated physical models compared to the scaled representation in CAD. For validity the process of producing the 12 models used the same parameters within the CNC software for all three materials and four scales. The experiment discovered unforseen aesthetic qualities in each of the three materials in relation to the relevant scales.

A comparison of the virtual environment (CAD) when viewing the site model on the computer screen with the physical scale models produced by the CNC Router identified design limitations of CAD when comparing the digital site model with the parameter settings of the CNC Router. The limitations were due to the set parameters of the CNC Router controlling the output of the site model through the incapability of the machine to perform the required instructions modelled in CAD. A significant factor was the designer visually identifying an unforseen quality revealed due to the restricted capabilities of the CNC Router because it is programmed to follow set parameters. This restricted ability can have positive outcomes as they can be viewed as added aesthetic qualities. This shows that the designer cannot always predict that the machined output will exactly replicate the design modelled within CAD.

\(^2\) CNC Router software is a CAD output programme that instructs the CNC Router to manufacture the CAD data.
These images display the comparison of the physical and digital representation of the three materials tested.
Evaluation of the Physical Scale to the Digital

The next stage in the experiment examined the 12 models compared to the virtual representation, focussing on the significance of scale. A key factor was that the digital 1:1 representation of the site model did not change its visual qualities when reduced in scale within the virtual environment. This stage of the experiment focussed on analysing the physical boundary of scale of the models in relation to the effects of the physical properties of the materials.

The boundary of scale was analysed by two factors: how the site model was created in the digital environment; and the set parameters of the CNC Router. The visual observation identified that the boundary of scale across the three materials produced two different results, a reduction in the predicted qualities and unforeseen aesthetic qualities revealed through the set parameters of the CNC Router. Figure 010 illustrates the comparison between the digital representation, the CNC software output preview and the physical output produced by the CNC Router. The figure shows a distinct difference between the CAD digital representation and the physical output of the CNC Router at the same scale. This was due to the restrictive capabilities of the CNC Router’s set parameters to produce a result consistent with CAD.

The reduction of scale forms a misrepresentation of the original scale within CAD. Within the reduction of scale the set parameters of the CNC Router generated a further aesthetic quality not predicted by the designer when comparing the digital representation to the physical model, this aesthetic quality is considered by the designer to add value to the process of creating a final outcome.

Traditional modelling methods use layered material to form the topography of physical scaled models as a visual representational tool. The aesthetic quality generated by the CNC Router in this experiment has advanced the production techniques when formulating physical site models. The experiment found that the layered topography used as a physical modelling technique can be successfully modelled within CAD. The significant difference occurred when reducing the scale of the geometry and
outputting this from CAD to the CNC Router. During this manufacturing stage the set parameters of the CNC Router manipulated the CAD geometry to create a smooth topography.

**Physical Model 3D Scanned into Digital Environment**

To maximise the smooth topography produced by the CNC Router the 12 physical models were 3D scanned into the virtual environment. Visual analysis of the CAD smooth topography mesh generated by the 3D scanner identified MDF as the most suitable material at a scale of 1:11500. However this did not achieve a satisfactory representation of the scaled built environment.

The designer then explored the possibility of using the smooth topography produced by the CNC Router to create a new scaled site model as a true representation of the built scaled environment. The properties of the MDF at 1:11500 were rescaled to 1:2000 in the virtual environment. The 1:2000 scale was selected as it fitted closely with the parameters of the CNC Router and the stock material to complete the process of assembling the final scale site model. Ciba-Tool was selected as the stock material as tests found that it generated a better surface finish than the other two materials at the new scale of 1:2000.

The layered topography was deleted from the original CAD site model and replaced by the smooth topography generated by the CNC Router at a scale of 1:2000. Figure011 displays the process of combining the smooth topography with the original site model within the virtual environment.

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3D scanning refers to the input of physical models into the digital environment.

4 Stock material is material applied at a given size to the CNC Router to construct the physical model.
These images illustrate the transition between the 3D scanned physical site model and reconnecting the machine aesthetic qualities with the original CAD site model.
Physical assembly of 1:2000 site model produced by CAM and CAD assistance.
Production of 1:2000 Physical Site Model

The next stage was production of the 1:2000 physical site model by breaking down the components of the CAD geometry into units that could be manufactured through CAM. The digital site model consisted of three components: the contoured topography mesh that had been 3D scanned and rescaled; a laser-cutter, which produced the base and network connections; and the built environment. The built environment was separated using CAD assistance into independent units. These units were then manufactured by the CNC Router. A manual assembly process undertaken by the designer then reconnected the three components. Documentation of the assembly process for the final 1:2000 site model and the construction process for all site models developed in this experiment is outlined in appendix _A pg. 6-55

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5 Laser-cutter is a machine used in CAM.
Figure 013: Experimentation Processes for Experiment 002

EXPERIMENT_002

- Components of 1:2000 Site Model
  Extracted from CAD Geometry

- Identifying CNC Router
  Aesthetic Surface Quality

- Identifying Generative System
  within Set Parameters of the CNC Router

- Aesthetic Surface Qualities
  Produced by Misrepresentation Process

- Abstract Object Created by
  CNC Router

- Physical Generative System
//{Experiment 002}//

Manufacturing Misrepresentation Process

Introduction

This experiment explored the second and third research objectives if these physical objects reveal unforseen aesthetic qualities not predicted by the geometry created in the three-dimensional environment and if the qualities produced by the CNC Router can be used as a practical conceptual design tool. To achieve the objectives the experiment explored a CAM method of subtraction revealing aesthetic qualities of an abstract nature utilising the CNC Router. The understanding of the CNC Router and the machine manufacturing processes obtained through experiment 001 was further explored in experiment 002 to establish if the CNC Router can be used as an architectural conceptual design tool. Figure 013 is a visual representation of the stages of the first experiment.

In experiment 002 the architectural model is referred to as an abstract object. The change in terminology is due to the research now exploring abstract creativity of the CNC Router as an architectural conceptual design tool.
These illustrations display the extraction process of the component mesh from the CAD 1:2000 site model produced in experiment 001.
Components of 1:2000 Site Model Extracted from CAD Geometry

To undertake experiment 002 the process established in experiment 001 of reconnecting the designer, CAD and the CNC Router is utilised. To create the physical objects, geometries were needed to explore different aesthetic qualities that can be manufactured by the CNC Router. Three 50x50mm geometries were extracted from the 1:2000 digital site model for use as components to apply to the CNC Router to further understand aesthetic qualities produced in the machine manufacturing processes.
1. Fine tool cut
2. Draft tool cut
3. Misrepresentation draft tool cut
4. Misrepresentation draft tool cut applied to all six surfaces.

This image identifies the CNC Routers aesthetic surface quality and how it has been furthered in the experimentation 002.
Identifying CNC Router
Aesthetic Surface Quality

To manufacture the CAD geometry using the CNC Router there are two manufacturing processes within the machine’s set parameters, a draft tool cut and a fine tool cut. The draft tool cut was selected based on the knowledge gained of the CNC Router in experiment 001.

The three geometries were then applied to the CNC Router as variables\(^6\) displaying a further range of aesthetic qualities produced by the draft tool cut. The aesthetic qualities generated by the draft tool cut are recognised as surface treatments applied to a geometry generated by the CNC Router but not recognised directly as three-dimensional physical objects.

The next stage was to break the boundary of resistance of the surface treatment of the CNC Router. This was done by rotating the material on axis to penetrate the surface creating extrusion through both surfaces and generating double-sided physical components. This revealed the potential to create a physical three-dimensional object that can be penetrated on all axis using qualities and attributes of the CNC Router draft tool cut. This identified architectural aesthetic qualities produced by the draft tool cut that can be used to further explore production of a physical abstract object.

\(^6\) Variables - multiple geometries extracted from the 1:2000 site model that were applied to the CNC Router.
These diagrams display a range of cross sections through the models displaying the limitations of the drill bit in relation to performing the required task of constructing the geometry applied to the CNC Router software.
Identifying Generative System Within Set Parameters of the CNC Router

The next stage in the experiment was to advance the aesthetic surface qualities produced by the CNC Router through the draft tool cutting process. To achieve this the designer engaged directly with the set parameters of the CNC Router and created a physical generative system. This differs from a traditional modelling technique of ‘modelling through series’ whereby the designer engages directly with the CAD geometry to produce aesthetic qualities.

This was done by misleading the CNC Router in the manufacturing processes when creating the surface aesthetic. Misleading refers to the designer engaging with the CAD CNC Router software and the physical set parameters of the machine. The designer instructed the CAD software that the CNC Router had a 6mm drill piece and the designer then applied a 3mm drill piece to the physical parameters of the machine. The reason for misinforming the machine was to improve upon the aesthetic qualities produced by the draft tool cut. If the CNC Router software had not been misinformed the machine would have defaulted to error before the manufacturing process began.

The significance of misleading the CNC Router is that the machine did not follow the fixed pre-set parameters of the geometry, instead the machine created an advanced aesthetic quality due to the designer’s manipulation of the draft tool cut. This revealed a physical surface with aesthetic qualities produced by the CNC Router manufacturing process. Figure016 displays the misrepresentation of the draft tool cut.
This image shows the aesthetic surface qualities produced in experiment 002. These models display a range of effects that can be created through the misrepresentation process.
Aesthetic Surface Qualities
Produced by
Misrepresentation Process

The designer further explored the application of misrepresentation by undertaking a series of tests on different geometry surfaces. The geometries were components of the 1:2000 site model and all had different surface characteristics in relation to the built environment. It was ascertained when applying the misrepresentation process that different aesthetic surface qualities could be created when varying geometries were applied to the CNC Router. Documentation of the construction process for each model, including the experimentation data, is contained in appendix_B pg. 56-183
This image displays the abstract object created in experiment 002 using a smoothened contour mesh extracted from experiment 001.
Abstract Object Created by CNC Router

The designer explored how the physical aesthetic surface treatment can be applied to the stock material (Ciba-Tool) to advance the ability of the CNC Router to create a three-dimensional abstract object. This was achieved by further breaking the boundary of resistance of the CNC Router to advance from a double-sided surface treatment to a machine inspired process applied to all six surfaces.

The three geometries extracted from the 1:2000 site model were used to produce three physical abstract objects. The misrepresentation process subtracted the material from all six surfaces of the stock material. Because of the aesthetic qualities identified previously the subtraction process generated three different physical abstract objects. Refer to figure017 for the process to generate a physical abstract object.
Multiple geometries used within generative design system to create three different physical abstract objects.
Physical Generative System

The processes of the experiment so far have informed the grammar to apply to create a physical generative system producing unforeseen abstract objects created by the CNC Router.

In applying the physical generative system the designer engaged with three key instructions when generating the physical abstract object. Firstly the type and size of the stock material was set at the maximum height allowed within the set parameters of the CNC Router at 50x50x50mm. Secondly the digital parameters applied to the CNC software and the physical parameters applied to the CNC Router were set. These digital and physical parameters made up the applied misrepresentation process, which was sent to the CNC Router and applied to all six surfaces. The final instruction was to rotate the material on axis six times after the completion of each phase of the misrepresentation process.

The experiment identified the ability to create an abstract object through the physical generative design system manufactured by the CNC Router. To view the construction processes of the multiple geometries applied as set variables to the physical generative design system refer to appendices.

The significance of using this physical generative design system is the transformation between the geometry applied and the relationship that geometry has to the physical abstract object. With this method applied, the relationship between the CAD 1:2000 geometry and the physical abstract object is the translation of scale to 1:1, this object only exists as a physical form with the geometry becoming an archive to the process.
Figure 020: Experimentation Processes for Experiment 003

EXPERIMENT_003

Reinterpreting the Object within the Digital Environment

Physical Aesthetic Quality Generated within the Set Coded Software

Allocation of New Given Stock Material

Assembly Architectural Detailing System

Reintroducing CNC Router Tooling into the Buildable Form

Reintroducing CNC Router Tooling into the Buildable Form
Design Outcome Formulating to the Buildable Form

Introduction

This experiment explored the fourth research objective; if the abstract expression produced by the CNC Router can formulate into a buildable form. To achieve the objective the experiment explored how conceptual qualities produced by the CNC Router can be used as an architectural thinking mechanism and how this can be formulated into a buildable form. The focus was on the aesthetic qualities generated by the CNC Router and how, by the use of both CAD and CAM, the designer could formulate a design outcome of the buildable form at a new 1:1 scale. The abstract object in experiment 003 is referred to as the buildable form. The change in terminology was made because this experiment explored conceptual creativity formulating to a buildable form.
Figure 021: Reinterpreting the object within the digital environment
Reinterpreting the Object
Within the Digital Environment

The first step taken to advance conceptual qualities to a buildable form was to explore a range of construction techniques. This was undertaken by relocating the scale of the 1:1 physical abstract object from experiment 002. The size selected by the designer, 2400x2400x2400mm, was in relation to customary stock material size used for architectural 1:1 construction within the built environment.

The physical abstract object manufactured by the CNC Router was 3D scanned creating a digital representation of the physical abstract object. However the outcome of this was that the physical abstract object interpreted by the 3D scanner produced different aesthetic quality than what was originally produced by the CNC Router. This process used the same application as experiment 001 but with a different result. The difference being the breaking of the boundary of resistance in experiment 002 which created a complex abstract three-dimensional object which the 3D scanner was unable to reconstruct as a digital representation. The consequence was the exact geometry of the physical abstract object was not reproduced therefore restricting the interpretation and evaluation of the digital representation. Therefore a new process was generated allowing the designer to interpret the aesthetic quality of the physical abstract object within CAD as a conceptual object to be formulated into the buildable form.
This image displays the thinking process of the user within CAD coded software to extract the internal geometry to reveal a hidden quality only identified in experiment 003.
Physical Aesthetic Quality Generated Within the Set Coded Software

This new process analysed the CNC Router’s subtraction techniques and these were adapted to the CAD parameter systems to generate a new form of subtraction technique mirroring the process of the CNC Router. This created a true representation of the physical abstract object as a digital representation.

Modern architectural design processes within CAD enabled the designer to successfully relocate the size of the digital representation the new size of 2400x2400x2400mm. Through this process new unforeseen qualities not foreseen by the designer emerged when visually analyzing the original physical abstract object. CAD systems identified these unforeseen internal and external qualities at the new located scale.

An advantage of using CAD systems, which is not within the capabilities of the CNC Router manufacturing process, is the manner in which the internal stock material is removed to reveal the unforeseen quality of an internal environment within the digital abstract object. An additional advantage of using CAD systems at this stage was the flexibility given to the designer to extract and modify the internal matter of the geometry. The digital representation advances the designer’s thinking mechanism to enhance the formulation of the buildable form. This is due to the new process introducing the physical abstract object into CAD design systems.
These images display the editing process within the coded software and the efficiency of using a given stock material size to further edit the digital abstract object to the buildable form.
Allocation of New Given Stock Material

To explore the translation of the digital object to a buildable form a newly assigned physical stock material was allocated to assist the designer in formulating the editing process of the digital object within CAD. The chosen stock material was milled pine timber set at 90x70mm.

The significance of using the editing process within CAD is the ability to edit the digital object and at the same time retain the aesthetic value of the physical abstract object when formulated into the buildable form. This is an application of the thinking mechanism of the designer in relation to the importance of staying true to the aesthetic qualities of the physical abstract object.

As mentioned previously the CAD software revealed internal and external qualities of the buildable form. Through the editing process the newly assigned stock material gave further aesthetic qualities to the interior and exterior appearance of the buildable form.
This illustration displays the physical object 1:50 3D print and the proposed architectural detailing system used to connect the new physical stock material of the buildable form.
Assembly of the Architectural Detailing System

At this point the developed buildable form exists within the virtual environment (CAD), which does not account for the materiality and structural physical forces involved when constructing the physical form. Therefore to take the geometry into a physical buildable form a construction detailing system was developed so the material formulating the buildable form could be assembled. This was undertaken by three-dimensional printing the original digital representation of the abstract object at a new scale of 1:50.

From the aesthetic qualities produced by the three-dimensional printer the designer’s thinking mechanism interpreted the chosen stock material to generate the physical detailing system of the buildable form. Refer to figure024. To avoid adding an additional aesthetic quality not developed in the physical abstract object the detailing system was designed to work in conjunction with the aesthetic quality of the stock material (pine) to add value to the buildable form rather than detracting from it.
Figure 025: Reintroducing CNC Router Tooling into the Buildable Form

Production Process of 4.5 Axis CNC Router

Draft Tool Cut Applied to Timber Detailing

CAD Geometry Applied to Aesthetic Detail

CAD CNC Milling Software Output Program
Reintroducing CNC Router Tooling into the Buildable Form

The aesthetic qualities left by the tooling process in experiment 002, which were generated by the CNC Router, were lost in experiment 003 in the translation between the physical abstract object and the digital representation within CAD. Refer to figure025.

This tooling process, which was once an archive to the formulation of the buildable form, was reinstated by the designer’s thinking mechanism as an aesthetic detail to the buildable form by utilising CNC Router manufacturing techniques. Documentation of the CNC Router generative tool path aesthetic technique including the experimentation data is contained in appendix_D.
This image displays the final buildable form constructed by the designer. The object is illuminated from the interior displaying the qualities of the expressive form and its relationship to true scale.
Production of the Buildable Form

At this point in the experiment the required data of the geometry of the buildable form was extracted from the CAD software and translated from a digital representation to the physical representation of the buildable form. Using CAD digital modelling techniques enabled the designer to extract two-dimensional drawings from the geometry constructed within the CAD software. The two-dimensional drawings formulated the construction process by using modern architectural construction communication to generate the buildable form. Documentation of the construction process including the working drawings, three-dimensional digital representation of the buildable form, and photographic and video documentation to formulate the buildable form is contained in appendix C pg. 183-207. An evaluation of the construction process of the design outcome in relation to the research question follows in the conclusion chapter five.
This image displays the external illumination of the form and the added effects this can have to the qualities expressed through the materiality of the interior space.
This image shows the final detailing system translated into the buildable form.
These images display the relationship between the CNC Router aesthetic qualities given back through the manufacturing process of the buildable form and how it has restored value to the draft tooling marks left behind in the original abstract object.
This image displays the internal spatial qualities identified through the CAD evaluation leading to the buildable form and its relationship to true scale.
Conclusion

Research Question and Summary of Supporting Arguments and Evidence

The findings from the experiments will inform a discussion on the linkage between the design process, architectural practice and the research question: What is the potential of utilising CAM technology for conceptual creativity formulating to a buildable form?

The methodology used to achieve the aim of the research was physical practical experimentation. The research findings support the research aim, which was to explore: the relationship between CAM and the methods of extracting and producing objects of a conceptual nature through CNC machine manufacturing techniques and how this could advance conceptual creativity formulating to a buildable form. The designer’s interpretation of the findings of the experiments is discussed below in the context of the research objectives.

The first objective was to explore; if what constitutes craft is present in the application of CAM. To address this the first experiment investigated the possibilities of closing the gap between the designer (craftsman) and machine (architectural tool), and reconnecting the point of detachment thereby returning control to the designer and the manner in which they control their tools. The research identified that with CAD assistance the construction process of the machine could be fractured, that is, the components making up the model could be separated during the point of detachment between print and creation. The components can then be reassembled to generate the vision of the designer. A significant outcome of this process was the unforeseen aesthetic quality produced by the CNC Router. This took the form of the topography of the original site that was 3D scanned back into the computer. This became a machine generated quality in the final model.

In relation to craft this connection established between conceptual design and the physical output of the model is supported by Rissati and McCullough. Rissati (2007) considers that it is ‘practical physical function’ that fuses what otherwise would be separate areas of activity, and this can help understand unique features of both
traditional and contemporary craft. McCullough (1996) refers to craft as where the designer applies standard coded software to apply variables to set parameters within the coded software to produce multiple unforeseen results. He sees computer geometric modelling as crafted when the designer employs limited pre-packaged software capacities inventively and creatively.

If the development of an understanding of the CNC Router had not been undertaken during this research, the research would have then relied more on the CAD digital fabrication qualities rather than the machine qualities produced by the CNC Router. Without connecting the machine to the designer the outcome of this research would have produced more digital fabricated qualities as opposed to machine qualities. This reinforces the reconnection that has been established between the craftsman and modern architectural tools. This finds support from Piano (as cited in Schodek et al., 2005) who says that CAD can be superficial and the design can be insufficiently resolved when it is studied only in its graphic form.

The outcome of experiment 001 is closely related to the modern applications of CAM that are available to architectural practice when developing conceptual design ideas. McCullough (1996) discusses how as part of developing more appealing technology there must be an understanding of what matters in traditional notions of practical form giving work. To be able to undertake this engagement requires some study of tools, human interaction and practicing the digital medium (CAD). These three components mentioned by McCullough were identified in experiment 001 and applied in experiment 002 where: the tool refers to the CNC Router; the human interaction is the engagement by the designer; and the digital medium is the geometry applied to the CNC software.

The findings of experiment 001 led to experiment 002, which explored the objective: if these physical objects reveal unforeseen aesthetic qualities not predicted by the geometry created in the three-dimensional environment. To achieve this, experiment 002 investigated how the extraction of geometries from a site model assisted the understanding of aesthetic qualities produced in the machine
manufacturing processes. A finding of experiment 002 was that the draft tool cut made by the CNC Router could be used to further explore production of physical abstract objects. Aesthetic qualities produced when using CNC manufacturing is a field of research identified with the work of Greg Lynn. Instead of smoothing out the traces of fabrication Lynn uses the stepping of the router bit to texture the surfaces and accentuate the curvature of surfaces (Rappolt, 2008). Lynn’s translation of surfaces into tool paths focuses on aesthetic qualities on a given surface. Lynn’s aesthetic process has not been developed further within conceptual architectural object modelling. The research has been informed by Lynn.

The research expanded on Lynn’s work through an application that misled the digital and physical parameters of the CNC Router creating a more dynamic expression of the draft tool cut. The significance of this was the identification of an extraordinary expression of tool paths, which is an aesthetic quality only produced through the machine manufacturing processes of the CNC Router. This led to the third objective, also investigated in experiment 002, to explore; if the qualities produced by the CNC Router can be used as a practical conceptual design tool. The ideas of Mitchell (1977) and McCullough (1996) influenced the development of the design process of the research in experiment 002. Mitchell (1977) refers to generative design systems and how a computer program operating under a data structure which models a design can constitute a generative system. McCullough (1996) refers to craft where the designer applies standard coded software to apply variables to set parameters within the coded software to produce multiple unforeseen results.

The point of difference in this research is that Mitchell and McCullough refer to design processes within CAD, whereas this research has taken the concept of a generative system and developed a physical generative system by using variables to set parameters to create multiple unforeseen results utilising the CNC Router. This was achieved in the experiment by breaking the boundary of resistance from a double-sided surface treatment to the point of difference generating a six-sided surface treatment, revealing an object expressing machine processes as an aesthetic quality. The
process developed in the experiments integrated the variables of materiality and the ability to change the geometry applied to the CNC Router. The significance is that the process developed by the designer established that the CNC Router could be used as a conceptual design tool when creating architectural objects or models.

The findings of experiment 002 led to experiment 003 which explored the fourth objective; if the abstract expression produced by the CNC Router can be formulated into a buildable form. The focus was on the abstract object generated by the CNC Router and how, by the use of both CAD and CAM, the designer could formulate a design outcome of the buildable form at a new 1:1 scale. The importance of using this abstract object as a thinking mechanism is outlined by Smith (2004) with respect to how models are used in the design process to express the meaning and the technique of the architect’s thinking and how they explore and define the unidentified and develop unforeseen conclusions. Smith’s thinking mechanism underpinned the designer’s decision making when translating the abstract object into the buildable form.

The first stage of experiment 003 was reinterpreting the object within the digital environment. A significant finding was that 3D scanning could not always produce a digital representation of the conceptual design idea. A consequence of this was that the designer created a new digital design process using generative systems to mirror the manufacturing processes created by the CNC Router, in turn producing a digital representation of the physical object. Mitchell (1977) states that generally a generative system does not directly create the actual object sought but instead it creates a representation model or design for the object, which then can be translated into the physical form. The importance of this finding that is consistent with Mitchell (1977) is that a generative system needs to be integrated into the design process through CAD when visually translating conceptual design ideas into a buildable form at a new scale.

This stage of the experiment realised Guthrie’s (2005) paradigm that abstractions are limited within the realm of scale and materiality, and that conceptual processes need to be kept open-ended as predetermined
ideas can change when they meet the physical reality.

A significant finding was that when relocating the digital representation to the new allocated scale an unforeseen quality was produced within the CAD environment when compared to the original physical object. This process also revealed that within the transition of scale the digital object revealed an internal environment in addition to the external environment.

When editing and evaluating the generative system of the digital representation it was revealed that a new stock material was needed. The significance of the editing process is the allocation of the new stock material and the translation of that material within the designer’s thinking process to formulate the translation of the digital abstract object to the buildable form. This editing process established a connection between the new digital process and the physical fabrication process to reveal the physical buildable form. This is consistent with Pottmann et al. (2007) discussion on how the choice of stock material plays a critical part in the design process in aesthetics of the final object. Also Guthrie (2005) sees the issue of confronting material reality as fundamental to architectural practice, but concedes there are areas of architectural thinking that denies or avoids material reality.

Pottmann et al., (2007) discusses how digital model making can use the same information used for fabricating the final building. This informed the evaluation of the final physical buildable form. This evaluation visually analysed the physical buildable form in relation to the digital interpretation created in CAD design systems. A significant finding was that the CAD representation could not interpret the materiality of the built form meaning that the material reacted differently to the process than expected. Certain locations on the object were disfigured in relation to the digital representation. This signifies the importance of materiality when translating conceptual design ideas to physical objects. The experimentation processes also revealed the significance scaled representation has when translating between the digital environment when exporting to physical scaled objects produced by the CNC Router. This leads to the evaluation of the buildable form in relation to the relocation of the 1:1.
scale. Moon (2005) highlights the importance the scale model has when fabricating the final building.

Experiment 003 establishes the relationship between the original physical abstract object and the new built form that signifies the designer’s thinking process. The role physical conceptual models traditionally had in developing architecture have been lost through the introduction of CAD generated design systems. This is because the modern applications of CAD create digital archives to the design process. Another significant finding of experiment 003 was that physically construction of the buildable form led to the transition of scale from the original abstract 1:1 object, which then became an archive to the design process by relocating the 1:1 scale to the buildable form.
Implications, Limitations and Possible Future Research Topics

Within architectural practice CAD is well established as an architectural design and documentation tool, on the other hand CAM and the use of CNC machines remain relatively under-utilised. This research has explored the use of CAD and CAM within design processes, identifying possible implications for architectural practice. CAM technology and CNC machines could add value to everyday architectural practice through cost effectiveness and efficiency by making desktop CNC Routers available within architectural practice thereby increasing design possibilities. The physical model produced by CAM and CNC machining when used in conjunction with CAD systems can add value to the conceptual design stage, which can lead to enhancing the built form. An example being the physical generative system designed in this research, which can create multiple design opportunities to be used as thinking mechanisms in architectural practice. A theoretical implication is that the processes developed in the experimentation stage could contribute to an academic module teaching CAM and CNC machine technological theory by practical application.

A limitation of the research was that it had to be contained within the course outline of an architectural professional Masters thesis. This meant that the research methodology had to be designed to fit with the time and resource constraints of the course programme thereby capping the scope of the research. As a fulltime student there were limitations on the financial resources available to support the cost of materials and use of the university CAM tools. Also there were limitations on the technology available within the university workshops.

The scope of the research was to achieve a physical built form. A possible future research topic could be to advance the design outcome to a resolved architectural building. There also could be further research by introducing additional computer-aided manufacturing tools thereby expanding the materiality and different manufacturing processes and the relationship these tools have to CAD and CAM design systems.
Design Process Leading to the Research Outcome

Figure 031: Design Process Leading to the Research Outcome
Conclusion

The researcher found that CAM production techniques with the assistance of CAD technology can produce an abstract object which can then be reinterpreted and formulated to a buildable form. However there were aspects of the experimentation process that were inconclusive. It was found that the physical abstract object could not be interpreted accurately through 3D scanning. This altered the aesthetic qualities of the buildable form. The process used by the researcher to overcome this did not achieve exact replication of the tooling qualities. The impact of this was that a unified connection between the physical object and the digital object was not achieved. It was considered that this did not invalidate the results of the experiments as the researcher was able to create a geometry that retained aesthetic qualities but with diminished tooling qualities. This indicates a need for further investigation into the process of inputting complex geometries into the three dimensional environment.

The variable aesthetic qualities produced in the experimentation process by CAD and CAM were open to interpretation based on the researcher’s individual perspective. However other individuals could have made different interpretations resulting in the final buildable form having varying visual qualities. This has raised the researcher’s awareness of the significance of individual interpretation when evaluating conceptual design possibilities.

Notwithstanding the implications of the aforementioned variable outcomes it is considered that the research may have contributed value to further understanding the potential of utilising CAM technology within the practice of architecture.
References


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Machine Actuated Craft

By
Jonathan William Murdoch

Appendix

Victoria University of Wellington
School of Architectural and Design
2010
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APPENDIX_A_001_1:15000

//{Visual Comparison of CAD Geometry to CNC-Router Preview}//

Figure 002: Comparing CNC software output to CAD Representation.
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Figure006: Comparing CNC software output to CAD Representation.
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Table009: Site Model Test Print001 _Ciba-tool_1:15000

//Set Parameters of CNC Software Output}//

APPENDIX_A_003_1:10500

//Visual Comparison of CAD Geometry to CNC-Router Preview}//

Figure010 Comparing CNC software output to CAD Representation.
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<tr>
<td><strong>Parameter Setting Y axis (Fine)</strong></td>
<td></td>
</tr>
<tr>
<td>Z axis Speed mm/ sec</td>
<td>5</td>
</tr>
<tr>
<td>X axis Speed mm/ sec</td>
<td>8.3</td>
</tr>
<tr>
<td>Path Spacing mm</td>
<td>0.15</td>
</tr>
<tr>
<td>Fine Margin mm</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table013: Site Model Test Print001 _Ciba-tool_ 1:15000

---

// {Set Parameters of CNC Software Output}//

**APPENDIX_A_004 1:10000**

// {Visual Comparison of CAD Geometry to CNC-Router Preview}//

Figure014: Comparing CNC software output to CAD Representation.
### Table 017: Site Model Test Print001 _MDF_ 1:15000

<table>
<thead>
<tr>
<th>Parameter Setting</th>
<th>X axis Speed mm/ sec = 6.3</th>
<th>Z axis Speed mm/ sec = 5</th>
<th>Y axis Speed mm/ sec = 8.3</th>
<th>X axis Path Spacing mm = 0.15</th>
<th>Z axis Path Spacing mm = 0.15</th>
<th>Y axis Path Spacing mm = 0.15</th>
<th>Duration of Production</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y axis</td>
<td>Fine Margin mm = 0.15</td>
<td>Fine Margin mm = 0.15</td>
<td>Fine Margin mm = 0.15</td>
<td>Fine Margin mm = 0.15</td>
<td>Fine Margin mm = 0.15</td>
<td>Fine Margin mm = 0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z axis (Draft)</td>
<td>2.5 mm cut</td>
<td>0.5 mm cut</td>
<td>0.25 mm cut</td>
<td>0.75 mm cut</td>
<td>0.75 mm cut</td>
<td>0.75 mm cut</td>
<td>2.5 hours</td>
<td>2.5 hours</td>
</tr>
</tbody>
</table>

**Material:** MDF

**Model Test Print001**

---

**APPENDIX A_005_1:15000**

**Figure 018:** Comparing CNC software output to CAD Representation.
| Table019: Construction G-Code |"
### APPENDIX_A_006_1:11000

//{Visual Comparison of CAD Geometry to CNC-Router Preview}//
// {Jonathan Murdoch_March592_2010} //
// {Jonathan Murdoch_March592_2010} //
// {Jonathan Murdoch_March592_2010} //
// {Jonathan Murdoch_March592_2010} //
// {Jonathan Murdoch_March592_2010} //
// {Jonathan Murdoch_March592_2010} //

// CNC-Router Construction Process //
// {Point of Detachment} // Ciba-Tool_Scale 1:1000

Table023: Construction G-Code
Figure024: Physical Site Model _1:11000
Material: **MDF**

<table>
<thead>
<tr>
<th>Scale</th>
<th>80% reduction in scale model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration of Production</td>
<td>Z axis (draft cut) = 4:43 hours</td>
</tr>
<tr>
<td></td>
<td>Y-X axis (fine cut) = 4:58 hours</td>
</tr>
<tr>
<td>Parameter Setting Z axis</td>
<td>Dia. mm. tool/ round head = 1.5</td>
</tr>
<tr>
<td>(Draft)</td>
<td>Z Speed mm/ sec = 0.5</td>
</tr>
<tr>
<td></td>
<td>Z Step mm = 0.625</td>
</tr>
<tr>
<td></td>
<td>X Y Speed mm/ sec = 12.8</td>
</tr>
<tr>
<td></td>
<td>Path Spacing mm = 0.75</td>
</tr>
<tr>
<td>Parameter Setting X axis</td>
<td>Z axis Speed mm/ sec = 5</td>
</tr>
<tr>
<td>(Fine)</td>
<td>X axis Speed mm/ sec = 8.3</td>
</tr>
<tr>
<td></td>
<td>Path Spacing mm = 0.15</td>
</tr>
<tr>
<td></td>
<td>Fine Margin mm = 0.1</td>
</tr>
<tr>
<td>Parameter Setting Y axis</td>
<td>Z axis Speed mm/ sec = 5</td>
</tr>
<tr>
<td>(Fine)</td>
<td>X axis Speed mm/ sec = 8.3</td>
</tr>
<tr>
<td></td>
<td>Path Spacing mm = 0.15</td>
</tr>
<tr>
<td></td>
<td>Fine Margin mm = 0.1</td>
</tr>
</tbody>
</table>

Table025: Site Model Test Print001 _MDF_ 1:10500

Figure026: Comparing CNC software output to CAD Representation.
### Material: MDF

<table>
<thead>
<tr>
<th>Parameter Setting Z axis (Draft)</th>
<th>Model Test Print004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter Setting X axis (Fine)</td>
<td>75% reduction on scale model</td>
</tr>
</tbody>
</table>
| Parameter Setting Y axis (Fine)  | Z axis (draft cut) = 5: 58 hours  
|                                  | Y-X axis (fine cut) = 7:10 hours |

#### Scale

- Dia. mm. tool/ round head = 1.5
- Z Speed mm/ sec = 0.5
- Z Step mm = 0.625
- X Y Speed mm/ sec = 12.8
- Path Spacing mm = 0.75

#### Duration of Production

- Z axis Speed mm/ sec = 5
- X axis Speed mm/ sec = 8.3
- Path Spacing mm = 0.15
- Fine Margin mm = 0.1

---

Figure030: Comparing CNC software output to CAD Representation.
### Table 033: Site Model Test Print001 _Plaster_ 1:15000

<table>
<thead>
<tr>
<th>Material: Plaster</th>
<th>Model Test Print001</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scale</strong></td>
<td>85% reduction in scaled model</td>
</tr>
</tbody>
</table>
| **Duration of Production** | Z axis (draft cut) = 2:45 hours  
|                    | Y-X axis (fine cut) = 2:56 hours |
| **Parameter Setting Z axis (Draft)** | Dia. mm. tool/ round head = 1.5  
|                    | Z Speed mm/sec = 0.5  
|                    | Z Step mm = 0.625  
|                    | X Y Speed mm/sec = 12.8  
|                    | Path Spacing mm = 0.75 |
| **Parameter Setting X axis (Fine)** | Z axis Speed mm/sec = 5  
|                    | X axis Speed mm/sec = 8.3  
|                    | Path Spacing mm = 0.15  
|                    | Fine Margin mm = 0.1 |
| **Parameter Setting Y axis (Fine)** | Z axis Speed mm/sec = 5  
|                    | X axis Speed mm/sec = 8.3  
|                    | Path Spacing mm = 0.15  
|                    | Fine Margin mm = 0.1 |

///{Set Parameters of CNC Software Output}///

**APPENDIX_A_009_1:15000**

///{Visual Comparison of CAD Geometry to CNC-Router Preview}///

Figure034: Comparing CNC software output to CAD Representation.
| Table035: Construction G-Code |

<table>
<thead>
<tr>
<th>Construction G-Code</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1;Z89,3116,4;Z0,3116,4;Z0,3116,20;Z0,3176,20;Z0,3176,4;Z12398,3156 - 12398,3136</td>
<td></td>
</tr>
<tr>
<td>42,2398,20,30;3642,20;3296,30;20,3296,30;20,3296,30</td>
<td></td>
</tr>
<tr>
<td>20,3256,20;20,3256,20</td>
<td></td>
</tr>
<tr>
<td>12;Z0,2876,20;Z0,2936,20;Z0,2936,-12;Z2398,2936,-12</td>
<td></td>
</tr>
<tr>
<td>12;Z0,2156,20;Z0,2216,20;Z0,2216,-12;Z2398,2216,-12</td>
<td></td>
</tr>
<tr>
<td>12;Z0,1626,18;Z0,1686,18;Z0,1686,-16;Z2398,1686,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,1226,16;Z0,1286,16;Z0,1286,-16;Z2398,1286,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,826,16;Z0,886,16;Z0,886,-16;Z2398,886,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,426,16;Z0,486,16;Z0,486,-16;Z2398,486,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,226,16;Z0,286,16;Z0,286,-16;Z2398,286,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,106,16;Z0,166,16;Z0,166,-16;Z2398,166,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,36,16;Z0,96,16;Z0,96,-16;Z2398,96,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,16,16;Z0,76,16;Z0,76,-16;Z2398,76,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,46,16;Z0,86,16;Z0,86,-16;Z2398,86,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,26,16;Z0,66,16;Z0,66,-16;Z2398,66,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,16,16;Z0,56,16;Z0,56,-16;Z2398,56,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,26,16;Z0,66,16;Z0,66,-16;Z2398,66,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,16,16;Z0,56,16;Z0,56,-16;Z2398,56,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,26,16,20;20,3642,20;3296,30;20,3296,30;20,3296,30</td>
<td></td>
</tr>
<tr>
<td>20,3256,20;20,3256,20</td>
<td></td>
</tr>
<tr>
<td>12;Z0,2876,20;Z0,2936,20;Z0,2936,-12;Z2398,2936,-12</td>
<td></td>
</tr>
<tr>
<td>12;Z0,2156,20;Z0,2216,20;Z0,2216,-12;Z2398,2216,-12</td>
<td></td>
</tr>
<tr>
<td>12;Z0,1626,18;Z0,1686,18;Z0,1686,-16;Z2398,1686,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,1226,16;Z0,1286,16;Z0,1286,-16;Z2398,1286,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,826,16;Z0,886,16;Z0,886,-16;Z2398,886,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,426,16;Z0,486,16;Z0,486,-16;Z2398,486,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,226,16;Z0,286,16;Z0,286,-16;Z2398,286,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,106,16;Z0,166,16;Z0,166,-16;Z2398,166,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,36,16;Z0,96,16;Z0,96,-16;Z2398,96,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,16,16;Z0,56,16;Z0,56,-16;Z2398,56,-16</td>
<td></td>
</tr>
<tr>
<td>12;Z0,26,16,20;20,3642,20;3296,30;20,3296,30;20,3296,30</td>
<td></td>
</tr>
</tbody>
</table>
### Table 037: Site Model Test Print001 _Plaster_ 1:11000

<table>
<thead>
<tr>
<th>Parameter Setting</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material: Plaster</strong></td>
<td><strong>Model Test Print002</strong></td>
</tr>
<tr>
<td><strong>Scale</strong></td>
<td>84% reduction in scaled model</td>
</tr>
<tr>
<td><strong>Duration of Production</strong></td>
<td>Z axis (draft cut) = 3:16 hours, Y-X axis (fine cut) = 3:19 hours</td>
</tr>
<tr>
<td><strong>Parameter Setting Z axis (Draft)</strong></td>
<td>Dia. mm. tool/ round head = 1.5, Z Speed mm/sec = 0.5, Z Step mm = 0.625, X Y Speed mm/sec = 12.8, Path Spacing mm = 0.75</td>
</tr>
<tr>
<td><strong>Parameter Setting X axis (Fine)</strong></td>
<td>Z axis Speed mm/sec = 5, X axis Speed mm/sec = 8.3, Path Spacing mm = 0.15, Fine Margin mm = 0.1</td>
</tr>
<tr>
<td><strong>Parameter Setting Y axis (Fine)</strong></td>
<td>Z axis Speed mm/sec = 5, X axis Speed mm/sec = 8.3, Path Spacing mm = 0.15, Fine Margin mm = 0.1</td>
</tr>
</tbody>
</table>

---

Figure 038: Comparing CNC software output to CAD Representation.
<table>
<thead>
<tr>
<th>Parameter Setting</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material: Plaster</td>
<td>Model Test Print 003</td>
</tr>
<tr>
<td>Scale</td>
<td>80% reduction in scale model</td>
</tr>
</tbody>
</table>
| Duration of Production | Z axis (draft cut) = 4:43 hours  
|                   | Y-X axis (fine cut) = 4:58 hours |
| Parameter Setting Z axis (Draft) | Dia. mm. tool/ round head = 1.5  
|                   | Z Speed mm/sec = 0.5  
|                   | Z Step mm = 0.625  
|                   | XY Speed mm/sec = 12.8  
|                   | Path Spacing mm = 0.75 |
| Parameter Setting X axis (Fine) | Z axis Speed mm/sec = 5  
|                   | X axis Speed mm/sec = 8.3  
|                   | Path Spacing mm = 0.15  
|                   | Fine Margin mm = 0.1 |
| Parameter Setting Y axis (Fine) | Z axis Speed mm/sec = 5  
|                   | X axis Speed mm/sec = 8.3  
|                   | Path Spacing mm = 0.15  
|                   | Fine Margin mm = 0.1 |

APPENDIX_A_011_1:10500

Visual Comparison of CAD Geometry to CNC-Router Preview

Table041: Site Model Test Print001_Plaster_1:10500

Figure042: Comparing CNC software output to CAD representation.
### Table 045: Site Model Test Print001 _Plaster_ 1:10000

<table>
<thead>
<tr>
<th>Material: Plaster</th>
<th>Model Test Print004</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scale</strong></td>
<td>75% reduction on scale model</td>
</tr>
</tbody>
</table>
| **Duration of Production** | Z axis (draft cut) = 5: 58 hours  
Y-X axis (fine cut) = 7:10 hours |
| **Parameter Setting Z axis (Draft)** | Dia. mm. tool/ round head = 1.5  
Z Speed mm/ sec = 0.5  
Z Step mm = 0.625  
XY Speed mm/ sec = 12.8  
Path Spacing mm = 0.75 |
| **Parameter Setting X axis (Fine)** | Z axis Speed mm/ sec = 5  
X axis Speed mm/ sec = 8.3  
Path Spacing mm = 0.15  
Fine Margin mm = 0.1 |
| **Parameter Setting Y axis (Fine)** | Z axis Speed mm/ sec = 5  
X axis Speed mm/ sec = 8.3  
Path Spacing mm = 0.15  
Fine Margin mm = 0.1 |

Figure046: Comparing CNC software output to CAD Representation.
Figure 049: Physical site models produced in experiment 001
Figure050: 1:2000 Physical Site Model
### APPENDIX_B_001

<table>
<thead>
<tr>
<th>Phase001</th>
<th>Model Test Print001</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scale</strong></td>
<td>Component of 1:2000 model Dimensions 50x50mm</td>
</tr>
<tr>
<td><strong>Duration of Production</strong></td>
<td>Z axis (draft cut) = 1:22 hours</td>
</tr>
<tr>
<td><strong>Program Parameter Setting Z/Y/X axis (Draft)</strong></td>
<td>Dia. mm. tool/ round head = 6mm Z Speed mm/ sec = 12 Z Step mm = 0.5 X Y Speed mm/ sec = 12 Path Spacing mm =2.2mm</td>
</tr>
<tr>
<td><strong>Machine Parameter</strong></td>
<td>Dia. mm. tool/ round head = 3mm</td>
</tr>
</tbody>
</table>

Figure051: Test Component_001_Ciba-Tool

Figure052: Cross section diagram of misrepresentation process_001

//{Cross Section of Misrepresentation Process Applied to CAD Geography}//
### APPENDIX_B_002

<table>
<thead>
<tr>
<th>Phase002</th>
<th>Model Test Print001</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scale</strong></td>
<td>Component of 1:2000 model</td>
</tr>
<tr>
<td></td>
<td>Dimensions 50x50mm</td>
</tr>
<tr>
<td><strong>Duration of Production</strong></td>
<td>Z axis (draft cut) = 1:22 hours</td>
</tr>
<tr>
<td><strong>Program Parameter Setting Z/Y/X axis (Draft)</strong></td>
<td>Dia. mm. tool/ round head = 6mm</td>
</tr>
<tr>
<td></td>
<td>Z Speed mm/ sec = 12</td>
</tr>
<tr>
<td></td>
<td>Z Step mm = 0.5</td>
</tr>
<tr>
<td></td>
<td>X Y Speed mm/ sec = 12</td>
</tr>
<tr>
<td></td>
<td>Path Spacing mm = 2.2mm</td>
</tr>
<tr>
<td><strong>Machine Parameter</strong></td>
<td>Dia. mm. tool/ round head = 3mm</td>
</tr>
</tbody>
</table>

Figure057: Test Component_002_Ciba-Tool

Figure058: Cross section diagram of misrepresentation process_002

//{Cross Section of Misrepresentation Process Applied to CAD Geography}//
### Table 059: Construction G-Code

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2;V11.6;Z1177,0,-29;V12.5;Z1425,0,-29;V15.0;Z1425,2098,7;Z1425,509,-29;Z15.0;Z1425,1929,43;Z12.5;Z1425,1929,43;Z11.6;Z1425,1929,43;Z10.5;Z1425,1929,43;Z9.0;Z1425,1929,43;Z7.5;Z1425,1929,43;Z6.0;Z1425,1929,43;Z4.5;Z1425,1929,43;Z3.0;Z1425,1929,43;Z1.5;Z1425,1929,43;Z1.0;Z1425,1929,43;Z0.5;Z1425,1929,43;Z0.25;Z1425,1929,43;Z0.125;Z1425,1929,43;Z0.0625;Z1425,1929,43;Z0.03125;Z1425,1929,43;Z0.015625;Z1425,1929,43;Z0.0078125;Z1425,1929,43;Z0.00390625;Z1425,1929,43;Z0.001953125;Z1425,1929,43;Z0.0009765625;Z1425,1929,43;Z0.00048828125;Z1425,1929,43;Z0.000244140625;Z1425,1929,43;Z0.0001220703125;Z1425,1929,43;Z0.00006103515625;Z1425,1929,43;Z0.000030517578125;Z1425,1929,43;Z0.0000152587890625;Z1425,1929,43;Z0.00000762939453125;Z1425,1929,43;Z0.000003814697265625;Z1425,1929,43;Z0.0000019073471328125;Z1425,1929,43;Z0.0000009536736660625;Z1425,1929,43;Z0.00000047683683303125;Z1425,1929,43;Z0.0000002384184165625;Z1425,1929,43;Z0.00000011920920828125;Z1425,1929,43;Z0.000000059604604140625;Z1425,1929,43;Z0.0000000298023020703125;Z1425,1929,43;Z0.00000001490115103515625;Z1425,1929,43;Z0.0000000074505755178125;Z1425,1929,43;Z0.00000000372528775890625;Z1425,1929,43;Z0.000000001862643878953125;Z1425,1929,43;Z0.0000000009313219394765625;Z1425,1929,43;Z0.00000000046566096973278125;Z1425,1929,43</td>
<td></td>
</tr>
</tbody>
</table>
Figure 060: Physical model test component_002_Ciba-Tool

Figure 061: Physical model test component_002_Ciba-Tool

Figure 062: Physical model test component_003_Ciba-Tool
APPENDIX_B_003

<table>
<thead>
<tr>
<th>Phase003</th>
<th>Model Test Print001</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scale</strong></td>
<td>Component of 1:2000 model Dimensions 50x50mm</td>
</tr>
<tr>
<td><strong>Duration of Production</strong></td>
<td>Z axis (draft cut) = 1:22 hours</td>
</tr>
<tr>
<td><strong>Program Parameter Setting Z/Y/X axis (Draft)</strong></td>
<td>Dia. mm. tool/ round head = 6mm Z Speed mm/sec = 12 Z Step mm = 0.5 XY Speed mm/sec = 12 Path Spacing mm = 2.2mm</td>
</tr>
<tr>
<td><strong>Machine Parameter</strong></td>
<td>Dia. mm. tool/ round head = 3mm</td>
</tr>
</tbody>
</table>

Figure063: Test Component_003_Ciba-Tool

Figure064: Cross section diagram of misrepresentation process_003

//{Cross Section of Misrepresentation Process Applied to CAD Geography}//
### APPENDIX_B_004

<table>
<thead>
<tr>
<th>Phase004</th>
<th>Model Test Print001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale</td>
<td>Component of 1:2000 model Dimensions 50x50mm</td>
</tr>
<tr>
<td>Duration of Production</td>
<td>Z axis (draft cut) = 1:22 hours</td>
</tr>
<tr>
<td>Program Parameter Setting Z/Y/X axis (Draft)</td>
<td>Dia. mm. tool/ round head = 6mm Z Speed mm/sec = 12 Z Step mm = 0.5 X Y Speed mm/sec = 12 Path Spacing mm = 2.2mm</td>
</tr>
<tr>
<td>Machine Parameter</td>
<td>Dia. mm. tool/ round head = 3mm</td>
</tr>
</tbody>
</table>

---

Figure069: Test Component_003_Ciba-Tool

Figure070: Cross section diagram of misrepresentation process_003

//{Cross Section of Misrepresentation Process Applied to CAD Geography}///
Figure072: Physical model test component_003_Ciba-Tool

Figure073: Physical model test component_003_Ciba-Tool

Figure074: Physical model test component_003_Ciba-Tool
### APPENDIX_B_005 Construction of Abstract Object_Ciba-Tool

#### Figure075: Test component_001_Ciba-Tool_Construction of abstract object_001

<table>
<thead>
<tr>
<th>Phase005</th>
<th>Print001</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scale</strong></td>
<td>Component of 1:2000 model Site Analysis Model Dimensions 10x50mm</td>
</tr>
<tr>
<td><strong>Duration of Production</strong></td>
<td>Z axis (draft cut) = 1.02 hours</td>
</tr>
<tr>
<td><strong>Program Parameter Setting Z/Y/X axis (Draft)</strong></td>
<td>Dia mm tool/round head = 6mm Z Speed mm/sec = 12 Z Step mm = 0.5 XY Speed mm/sec = 12 Path Spacing mm = 4.5mm</td>
</tr>
<tr>
<td><strong>Machine Parameter</strong></td>
<td>Dia mm tool/round head = 3mm</td>
</tr>
<tr>
<td><strong>Rotate Axis</strong></td>
<td>Dia mm tool/round head = 3mm Z Speed mm/sec = 12 Z Step mm = 0.5 XY Speed mm/sec = 12 Path Spacing mm = 0.8</td>
</tr>
</tbody>
</table>

#### Figure076: Cross section diagram of misrepresentation process_001

//{Cross Section of Misrepresentation Process Applied to CAD Geography}//
Figure 078: Series of models identified to create abstract object_001_Ciba-Tool

Figure 079: Series of models identified to create abstract object_001_Ciba-Tool

Figure 080: Series of models identified to create abstract object_001_Ciba-Tool
APPENDIX_B_006 Construction of Abstract Object_Ciba-Tool

Figure082: Cross section diagram of misrepresentation process_002

//{Cross Section of Misrepresentation Process Applied to CAD Geography}//
Figure 084: Series of models identified to create abstract object_002_Ciba-Tool

Figure 085: Series of models identified to create abstract object_002_Ciba-Tool

Figure 086: Series of models identified to create abstract object_002_Ciba-Tool
### APPENDIX_B_007 Construction of Abstract Object_Ciba-Tool

#### Figure088: Cross section diagram of misrepresentation process_003

- **Phase005**
  - **Print001**
  - **Scale**
    - Component of 1:2000 model
    - Site Analysis Model
    - Dimensions 50x50mm
  - **Duration of Production**
    - Z axis (draft cut) = 1.02 hours
  - **Program Parameter Setting Z/Y/X axis (Draft)**
    - Dia. mm tool/round head = 6mm
    - Z Speed mm/sec = 12
    - Z Step mm = 0.5
    - XY Speed mm/sec = 12
    - Path Spacing mm = 4.5mm
  - **Machine Parameter**
    - Dia. mm tool/round head = 3mm
  - **Rotate Axis**
    - Dia. mm tool/round head = 3mm
    - Z Speed mm/sec = 12
    - Z Step mm = 0.8

#### Figure087: Test component_002_Ciba-Tool_Construction of abstract object_003

//{Cross Section of Misrepresentation Process Applied to CAD Geography}//
Figure 090: Series of models identified to create abstract object_003_Ciba-Tool

Figure 091: Series of models identified to create abstract object_003_Ciba-Tool

Figure 092: Series of models identified to create abstract object_003_Ciba-Tool
APPENDIX_B_008 Construction of Abstract Object_Timber

<table>
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<th>Phase005</th>
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<tr>
<td>Scale</td>
<td>Component of 1:2000 model Site Analysis Model Dimensions 50x50mm</td>
</tr>
<tr>
<td>Duration of Production</td>
<td>Z axis (draft cut) = 1.02 hours</td>
</tr>
</tbody>
</table>
| Program Parameter Setting Z/Y/X axis (Draft) | Dia. mm tool/round head = 6mm  
Z Speed mm/sec = 12  
Z Step mm = 0.5  
XY Speed mm/sec = 12  
Path Spacing mm = 4.5mm |
| Machine Parameter  | Dia. mm tool/round head = 3mm                                             |
| Rotate Axis        | Dia. mm tool/round head = 3mm  
Z Speed mm/sec = 12  
Z Step mm = 0.5  
XY Speed mm/sec = 12  
Path Spacing mm = 0.8 |

Figure093: Test component_002_Ciba-Tool_Construction of abstract object_003

Figure094: Cross section diagram of misrepresentation process_003

Figure094: Cross section diagram of misrepresentation processApplied to CAD Geography
Figure096: Series of models identified to create abstract object_003_Timber x3

Figure097: Series of models identified to create abstract object_003_Timber x3

Figure098: Series of models identified to create abstract object_003_Timber x3

Figure099: Series of models identified to create abstract object_003_Timber x3
APPENDIX_C_001 CONSTRUCTION WORKING DRAWINGS
Figure 103: Cutting List_B02
SECTION C

PANEL 001

PANEL 002

01 02 03 04 05 06 07 08

01 02 03 04 05 06 07 08

09 10 11 12 13 14 15

09 10 11 12 13 14 15

CUT  CNC  Detail

CUT  CNC  Detail

Figure 104: Cutting List_C
SECTION D01

Figure 105: Cutting List_D01
Figure 106: Cutting List_D02
SECTION E

PANEL 001

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<td>□</td>
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Figure 107: Cutting List E
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Figure 108: Cutting List_F01
SECTION F02

PANEL 003

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SECTION A

Support Detailing Positioning

Figure 110: Support detail drilling list_A
SECTION B01
Support Detailing Positioning

Figure 111: Support detail drilling list_B01
SECTION B02

Support Detailing Positioning

PANEL 003

Figure 112: Support detail drilling list_B02
SECTION C

Support Detailing Positioning

Figure 113: Support detail drilling list C
SECTION D01

Support Detailing Positioning

PANEL 001

PANEL 002

Figure 114: Support detail drilling list D01
SECTION D02

Support Detailing Positioning

PANEL 003

Figure 115: Support detail drilling list_D02
SECTION E

Support Detailing Positioning

Figure 116: Support detail drilling list_E
SECTION F01

Support Detailing Positioning

Panel 001

Panel 002

Figure 117: Support detail drilling list F01
APPENDIX_C_002

//--{Visual Construction process of the buildable form }//--

Figure 119: Visual Construction process of the buildable form 001

Figure 120: Visual Construction process of the buildable form 002

Figure 121: Visual Construction process of the buildable form 003
Figure 122: Visual Construction process of the buildable form 004

Figure 123: Visual Construction process of the buildable form 005

Figure 124: Visual Construction process of the buildable form 006

Figure 125: Visual Construction process of the buildable form 007
Figure 126: Visual Construction process of the buildable form 008

Figure 127: Visual Construction process of the buildable form 009

Figure 129: Visual Construction process of the buildable form 010

Figure 130: Visual Construction process of the buildable form 011
Figure 130: Visual Construction process of the buildable form012

Figure 131: Visual Construction process of the buildable form013

Figure 132: Visual Construction process of the buildable form014

Figure 133: Visual Construction process of the buildable form015
Figure 134: Visual Construction process of the buildable form 016

Figure 135: Visual Construction process of the buildable form 017

Figure 136: Visual Construction process of the buildable form 018

Figure 137: Visual Construction process of the buildable form 019
Figure 138: Visual Construction process of the buildable form020