Digital Mould

Hybridizing digital-analogue fabrication techniques

by

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Abstract //

The subject of this thesis pertains to current digital fabrication and CAM (computer aided manufacturing) techniques in architecture. It is a response to the current condition of architectural fabrication in which design processes occur largely via digital means and construction techniques are still reflective of hand-made, manufactured, or hand-assembled processes. This thesis aims to answer the following question: How can complex computer aided design processes be better implemented by thinking of the design-fabrication process as a whole rather than as separate practices? Subsequently, this question will be explored through a bespoke design for a digital mould, which maintains the digital design intent allowing the author to maintain control of the exploration and final iteration of the work. Through the use of the digital mould, this thesis will explore possibilities of feedback between the digital model, and the properties of glass fiber reinforced concrete (GFRC) to create double curved concrete panels.

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1.0 - Preface //

1.1 - Introduction

1.2 - Significance

1.3 - Research method

1.4 - Scope of work

1.1 - Introduction //

Fig. 01
Sample of a panelized surface digitally
designed for the digital mould.

Within the profession of architecture, digital design has been universally accepted due to the advantages it possesses over traditional methods of design.⁰¹ However, despite the numerous virtues of digital design, often the construction techniques related to these designs remain reliant on hand-made, manufactured, or hand-assembled processes. This thesis is a response to this condition of architectural fabrication, and attempts to address the discrepancies between digital design and fabrication processes through the exploration and use of hybrid digital -analogue techniques. Accordingly, the project deals predominately with the design and construction of what will be termed a 'digital mould'. Dissimilarly to a traditional mould, the digital mould in question is an apparatus which has variable surface and edge conditions. This variability permits the mould to be digitally informed via CAD (computer aided design) processes. While the varying shape of the mould can be informed digitally, the adjustment of the mould and application of material remains a manual process. This digital mould will act as the means by which digital and analogue techniques are amalgamated and explored throughout the course of the thesis. Spray GFRC (glass fiber reinforced concrete) is explored as the medium applied to the digital mould. GFRC provides a low waste option for the mould, as it is an additive method. Furthermore, concrete proves to be a good material option based on its availability and wide use within the construction industry.⁰²

⁰¹ Sennett, Richard. *The Craftsman*. New Haven, London: Yale University Press, 2008. p.39

⁰² Lefteri, Chris. *Materials for design*. London: Laurence King Publishing, 2014. Print. p.212

This topic becomes increasingly relevant as architects find themselves often relying on computer aided design, as the standard method, to develop projects. At times, the precision and capability of CAD can be deceiving to designers as the tools and procedures within the digital sphere do not necessarily reflect the available fabrication tools and techniques. This distinction is often addressed through the post-appropriation of commonly used digital fabrication techniques, implemented with tools such as 3D printers and CNC machines (Computer Numerical Control). Through the design, construction and use of the digital mould, this thesis aims to explore alternative means of digital fabrication; ultimately circumventing the standard techniques for digital fabrication and expanding the realm of possibility allotted to the designer.

Fig. 02
Preliminary sketches exploring ideas of constructing double curved concrete panels.

1.2 - Significance //

How can complex computer aided design processes be better implemented by thinking of the design-fabrication process as a whole rather than as separate practices?

This question is significant due to the overarching shift towards methods of digital design and fabrication within the architectural community. This trend promotes the use of tools such as CNCs and 3D printers as a means to execute a digital fabrication process. Despite these tools being digital, they are not specifically informed by the original parameters of the desired product. While popular digital fabrication tools provide a gamut of variability, they are not necessarily optimized for the variable nature specified in the end product in instances where unique material alternatives might be desired. One common example is the use of digital fabrication to generate complex concrete forms. This challenge is most often approached by CNC milling a polyurethane-foam negative, creating a mould for the concrete. Here we have the design being altered according to the intentions and limitations of the tool . This often leads to compromised design intentions and/or wasteful fabrication techniques.

Alternatively, by treating the design to fabrication process holistically we can start to contemplate the role and consequence each part will have. By understanding the process in this way, we can redefine each component to better suit the end goal; fabricating a design which is consistent to the original design intent while considering other factors specified by the architect. Factors to consider range from material properties to waste generated during the fabrication process. This goal will be explored through the hybrid use of digital and physical techniques.

1.3 - Research method //

Due to the material nature of this thesis, research will be achieved through the careful study of literary work and architectural precedence accompanied by a research by design methodology. The research by design method can be described as “architectural and spatial design studies”.⁰³ The studies are not pertaining directly to architecture but rather to a broader realm of spatial examinations and their relation to architecture. The full scope of research can be thought of as the inquiry into partially amalgamated fields within the realm of architectural conception and production. These fields will range from digital design to hybrid digital-analogue fabrication techniques. The product of these hybrid techniques is the digital mould and its related set of prototypes (double curved concrete panels).

Fig. 03
Preliminary sketch exploring ideas of double curved forms.

⁰³ Traganou, Jilly. “Architectural and Spatial Design Studies: Inscripting Architecture in Design Studies.” *Journal of Design History* 22, no. 2 (June 2009): 173-81. Accessed December 14, 2016. doi:10.1093/jdh/epp009.

1.4 - Defining scope of work //

This thesis will focus on the relationship between digital design techniques and manufacturing techniques. The scope of work will be limited to a body of research accompanied by the construction of the digital mould and its related set of physical prototypes. These prototypes are double curved GFRC panels. Emphasis will be placed on digital design technique as a key component of the design-fabrication process. The scope of research is broken down into the following parts:

Literary research:

- + Digital design techniques
- + Current digital fabrication techniques
- + Case study illustrating viable digital fabrication process
- + Craft and traditional construction techniques
- + Physical form finding and material intuition
- + Current digital analogue hybrid-techniques

Research by design:

- + Designing and building a digital mould to explore digital-analogue hybrid techniques
- + Material prototypes to achieve basic proof of concept

2.0 - Techniques //

2.1 - Digital design

2.2 - Digital manufacturing

2.3 - Case study - UNStudio

2.4 - Form finding

2.5 - Craft

2.6 - Material behaviour

2.7 - Tools

2.1 - Digital Design //

Fig. 04
Sample of a preliminary algorithmic script developed for the digital mould.

Utilization of digital modeling has become ubiquitous within architectural design.⁰⁴ Under the umbrella of digital modeling exists subcategories closely defining modeling technique and function. Some of these subcategories include building information modeling (BIM), parametric modeling, algorithmic or procedural modeling and scripting base modeling. These digital modeling workflows all share common advantages over traditional design processes in regards to replicability of work and project archiving. However, digital modeling's most utilized strength is perhaps its capacity to enable access to a single master file, which facilitates multi-disciplinary efforts and consequent 'file-to-factory' production.⁰⁵ In the case of digital fabrication, the ability to reference one highly accurate source for data retrieval is essential in coordinating and executing complex architectural designs.

As we advance through the aforementioned digital modeling methodologies, we find ourselves drifting towards computationally driven design. Achim Menges refers to computational design as simultaneously being an opportunity and challenge to architecture.⁰⁶ He describes this challenge not as a technical one but rather as an adaptation of a new mode of thinking. It is common to assume that architects have fully acculturated computational design into their realm. However, Menges argues that "with very few exceptions, design computation still merely serves the purpose of extending or accelerating well established design processes".⁰⁷ Menges delineates the term computerization from computational by

⁰⁴ Sennett, Richard. *The Craftsman*. New Haven, London: Yale University Press, 2008. p.39

⁰⁵ Hensel, Michael, Achim Menges, and Michael Weinstock, eds. *Techniques and Technologies in Morphogenetic Design*. Vol. 76. London: Wiley, 2006. p.71

⁰⁶ Menges, Achim, and Sean Ahlquist. *Computational design thinking*. Chichester, UK: John Wiley & Sons Ltd, 2011. p.8

⁰⁷ Ibid.

Fig. 05
Example of a computationally generated form.

explaining that instances of computerization simply contain the information initially supplied, while something computationally generated contains additional information and detail not initially specified. Through the use of computational design architects are now capable of achieving formal complexities either not possible or not feasible in the past. In this sense, the use of ‘computational’ design in common practice does not reflect its true capacity or potential and is perhaps better described as computerized design. Despite the advancements made in digital modeling techniques, the physical building techniques to achieve these digital designs are inherently lagged behind. Konrad Wachsmann, was a German architect known for his contributions to modularization and production of standardized building materials during the mid-twentieth century (1949-1964).⁰⁸ Wachsmann argued that “each time the architectural production technology changes, the architecture changes as well”.⁰⁹ In the case of digital design this ‘change’ is not a means of production but rather a means of devising. In this way, we can understand its impact to permeate into production and then into architecture. Subsequently, in the attempts to construct complex digital designs, we often see a neglect of the production component of this equation. This neglect is most often realized in the form of post-appropriating production/fabrication techniques onto a design. In the case of the digital mould, the intention is to construct an apparatus which permits the construction of a particular digital design, a double curved concrete surface, without this post appropriation of technique and material.

⁰⁸ Hale, Jonathan A., John Stanislav Sadar, William W. Braham, and Taylor & Francis Group. 2007;2006;. *Rethinking technology: A reader in architectural theory*. New York: Routledge. p.119

⁰⁹ Agkathidis, Asterios, Johan Bettum, Markus Hudert, and Harald Kloft. *Digital Manufacturing In Design and Architecture*. Amsterdam: BIS Publishers, 2011. p.118

2.2 - Digital manufacturing //

Fig.06
Double curved surface and its corresponding waffle frame version.

In the current state of digital fabrication certain digital manufacturing techniques have become standardized in that they are commonly used. This standardization is in part reflective of the tools used to execute these techniques. Common tools such as laser cutters and CNC routers provide tangible solutions to complex digital designs, which may involve complexities such as double curved surfaces and intricate patterns. Some of these 'standardized' techniques include: cross segmentation (otherwise known as a waffle frame), accumulation (stacking layers) and sheet shape frameworks.¹⁰ Many of these techniques provide a portion of the desired traits within a design, but often lack the capacity to fulfill the original design intent. Take for instance the common technique of cross segmentation, which provides a tangible solution to the strenuous challenge of creating doubled curved surfaces. In utilizing this technique, the original form becomes segmented and rather than being left with a true surface we are left with the suggestion of one. In the case where this effect is not deliberate, it becomes a compromise of design intention.

Furthermore, these techniques are typically wasteful methods of fabrication as they are based on a subtractive method, meaning that material is taken away in order to create the desired product. Subtractive methods of construction are not new to architectural fabrication, however typical subtractive construction techniques are directly influenced and correlated to the qualities of standard materials. Standard materials such as nominal lumber and plywood are rectilinear, this is reflective of the typical tools and techniques of construction. Thus, the material is optimized to minimize waste, consequently

¹⁰ Agkathidis, Asterios, Johan Bettum, Markus Hudert, and Harald Kloft. Digital Manufacturing In Design and Architecture. Amsterdam: BIS Publishers, 2011.

50%

47%

55%

48%

Fig. 07
Recreated cut profiles with respective waste percentages.

making a more cost effective process. On the other hand, digital fabrication techniques such as cross segmentation and accumulation utilize novel reductive methods in conjunction with standardized materials. This can result in a high waste to product ratio in the case where curvilinear forms are cut from rectilinear materials. Take for instance the One Main Office Renovation, designed by dECOI Architects. This project involves the renovation of an office space using CNC machining techniques. Utilizing a CAD/CAM build process in conjunction with a procedural scripting process, the architects were capable of achieving complex bespoke forms in lieu of standard material assemblies.¹¹ Upon inspection of the cut profiles of One Main Office presented in *Digital Fabrication in Architecture*,¹² it is evident that a significant portion of the profiles account for negative space (waste). In recreating a few of the profiles it was calculated that the off-cuts or waste associated to each sheet was within the range of 40 - 55%.

Fig. 08
dECOI Architects / One Main Office Renovation, Cambridge, MA, 2009

¹¹ Dunn, Nick. *Digital Fabrication in Architecture*. London: Laurence King Publishing, 2012. p.136
¹² Ibid.

Antithetically, additive techniques provide an alternative means of constructing complex digital forms. Common additive digital manufacturing techniques are often referred to as rapid prototyping or 3D-printing. These methods of fabrication utilize the accumulation of successive layers of material to form the desired product.¹³ The primary advantage of additive techniques is the capacity to manufacture complex objects which would not be possible to build using subtractive methods. The complexities allowed by 3D-printing include internal spaces within homogeneous objects and encapsulated moving parts. Furthermore, by virtue of its technique, additive processes demonstrate a means of making with little to no waste byproduct. Among the available 3D-printing techniques the most popular prove to be SLA (stereolithography), SLS (selective laser sintering) and FDM (fuse deposition modeling).¹⁴ Due to their low waste production, these techniques shift the focus of construction technique optimization to form optimization, alleviating the weight of construction technique as a primary constraint of the fabrication process.¹⁵ Despite the multiple advantages digital additive techniques provide over subtractive techniques and traditional techniques they remain largely infeasible to general architectural constructions. This is primarily due to 3D-printing techniques having a high cost to product ratio. The high cost associated to 3D-printed parts is caused by size constraints on the part of the equipment, high equipment cost and relatively slow production.¹⁶ That being said, these techniques are generally reserved to smaller components and architectural models.¹⁷

13 Tedeschi, Arturo, Fulvio Wirz, and Stefano Andreani. AAD, Algorithms-aided design: parametric strategies using Grasshopper. Brienza, Italy: Le Penseur Publisher, 2014. p.316

14 Ibid., 317

15 Ibid., 319

16 Kolarevic, Branko, and Taylor & Francis Group. 2003. Architecture in the digital age: Design and manufacturing. New York: Spon Press. p.57

17 Ibid.

Fig. 09
Minibuilders - 3D printed concrete shell
(completed form)

Recently, however, there have been explorations with larger format 3D printing technologies which are compatible with concrete. Take for instance the Minibuilders project done at the Institute for Advanced Architecture of Catalonia in 2013.¹⁸ This project successfully uses multiple custom built robots in conjunction with specialized software to print a shell like structure. However, this technique of 3D printing seems to be subject to many of the same limitations present in consumer grade FDM (fuse deposition modeling) printing. The limitations of FDM printing relate primarily to the need for support material, as the forms are printed using thin additive layers, each layer can only shift in relation to the last layer by a limited amount.¹⁹ Without printing out additional support material, this layered construction restricts the deflections possible in the x and y axis's. This limitation becomes evident in the Minibuilders project as the printed structure is essentially a cylindrical projection with small incremental projections outwards. While 3D printed concrete technology seems promising, there is still room for improvement and for now it remains largely within the realm of academia.

Fig. 10
Minibuilders - 3D printed concrete shell (in progress)

¹⁸ "Minibuilders." Institute for Advanced Architecture of Catalonia. Accessed March 30, 2017. <https://iaac.net/research-projects/large-scale-3d-printing/minibuilders/>.

¹⁹ Tedeschi, Arturo, Fulvio Wirz, and Stefano Andreani. AAD, Algorithms-aided design: parametric strategies using Grasshopper. Brienza, Italy: Le Penseur Publisher, 2014. p.317

2.3 - Case study //

UNStudio, Arnhem Central station,
Arnhem, The Netherlands, 1996-2014

Fig. 11
Aerial view of Arnhem Central Station

This project is particularly relevant for this thesis as the materiality and formal approach relate greatly to the intended digital mould panels. The project involves the manufacturing of a double curved roof system comprised of glass fiber reinforced concrete (GFRC) panels, utilizing a CAD/CAM process to achieve a high level of accuracy.²⁰ Due to the exterior building form each panel must be custom made. Custom made GFRC panels are not exclusive to this project, take for instance the panels installed on Cooper Union for the Advancement of Science and Art building. What is unique in the case of the Arnhem Central Station is the approach taken to developing the modeling

²⁰ Ibid., 86

techniques used to generate the panels. Each panel is informed by fabrication parameters such as “maximum mould size, anchor locations and geometric efficiencies”.²¹ In this sense the final forms are reflective of key design constraints. This approach to computational modeling is more in line with the potential of computation previously mentioned by Menges.²² By customizing the digital design process itself the computer can be tasked with the innumerable operations necessary in calculating the details for each custom panel, something which would be infeasible, if not impossible, to do ‘by hand’. The process utilized in this project carefully curates the relationship between design and digital tool (algorithmic modeling in this case). This approach to algorithmic modeling can be applied to the digital mould as mould parameters can influence the digital design aspect of the thesis project.

Fig. 12
Bespoke panel profiles

²¹ Ibid.

²² Menges, Achim, and Sean Ahlquist. Computational design thinking. Chichester, UK: John Wiley & Sons Ltd, 2011. p.10

2.4 - Form-finding //

Fig. 13
Excerpt from a form generated using the mathematical logic of the inscribed square problem within an algorithmic modeling program (Grasshopper).

Within the architectural realm, form-finding and form-searching methodologies have become popular due to increase use of computer/algorithm-aided design . These methods of designing enable the architect to quickly explore numerous variable outcomes. What may be particularly appealing about algorithm-aided design is the inherent embedded mathematical logic present in the design algorithm; this seemingly gives reason to the sometimes random looking forms. Take for instance forms generated using the mathematical logic of the inscribed square problem. Here the architect is capable of choosing forms based on a purely aesthetic basis while continuously maintaining the justification for the appearance of the form: mathematical logic.

Does this truly translate to 'raison d'être' or are these forms better described as "improbably formed, informed objects"²³? Moreover, in regards to arbitrary digital form-finding, the architect is left with the task of appropriating construction techniques to a form which was not designed with a technique in mind. Alternatively, what if the embedded logic was not derived from abstract sources but rather derived from information pertaining to material characteristic or perhaps construction technique. This derived information could be inputted in the form of design parameters much like in the case of the Arnhem Central Station project .

²³ Flusser, Vilém. *Towards a Philosophy of Photography*. Reaktion Books, 2000. p.49

2.5 – Craft //

Fig. 14
Macro photography of sprayed concrete
test

As defined by Richard Sennett “all craftsmanship is founded on skill developed to a high degree”²⁴. Sennett’s perception is such that anyone dedicated to producing quality work constitutes as a craftsman and that the desire to do a job well done has merit in itself. Through Aristotle’s lens, there is a secondary understanding of craftsmanship as being deeply related to hand work or hand making²⁵.

In, *The Craftsman*, Sennett quotes an excerpt of Renzo Piano describing his design methodology. In his description, he articulates each step of the process as being distinct yet integral to the next, further explaining that steps are constantly revisited. Piano moves from drawing to making and back again, repeating this process, expanding on each iteration. This process of repetition and revisiting is later described by Sennett as ‘circular metamorphosis’²⁶. Sennett’s primary critique of using CAD methodologies is that this circular metamorphosis can be aborted, and that misuse will arise if the design software is not open to ease of reiteration. Still, much like Piano learnt to develop his own process for designing by hand, surely an iterative process could be applied to a CAD approach. Within the digital landscape, the role of the craftsman then, is to compensate for errors and inaccuracies in the work. As such, the process of the craftsman becomes that of continuous adjustments, creating a feedback-loop between intention and actuality.²⁷

²⁴ Sennett, Richard. *The Craftsman*. New Haven, London: Yale University Press, 2008. p.21

²⁵ Ibid.

²⁶ Ibid., 40.

²⁷ Hayes, James, David Edgar, and Phil Whyte. “Digital Craft.” Lecture, Open Forum , Azrieli School of Architecture & Urbanism - Carleton University, Ottawa, November 07, 2016

In the current state of three-dimensional modeling software, many programs attempt to simulate more intuitive ways of developing a model. These programs (such as Mudbox, and ZBrush) lend from craft based techniques such as clay modeling (additive) or sculpting (subtractive). In their attempts to create intuitive work-flows they find themselves simulating properties of physical tools such as brushes. These digital-tools speak to the past methodologies of hand-made techniques. Here we have digital tools simulating methods of working with the hand, in a way this could also be considered a simulation of the intuitive nature of crafting. Even in our digitally saturated world , the hand-made remains a critical factor and constraint within the design and construction industry. This point emphasizes the necessity for the inclusion of analogue techniques and manual control over the final product in the case of the digital mould.

Fig. 15
Sketch exploring ideas of how to manually articulate the digital mould surface.

2.6 - Material behaviour //

Fig. 16
Photograph of Josef Albers and an exploitative paper model.

Fig. 17
Photograph of Frei Otto soap bubble experiments.

Josef Albers is known for his work in material studies during the 1920s. What is interesting about Albers' approach to material exploration was his concept of deriving inspiration from material behaviour rather than from previous conceptions and methods of working with materials. With this approach, Albers was capable of foregoing the already established construction methodologies utilized within the architectural profession and propose new ways of looking at materials²⁸. Albers' work is regarded as the precursor to generative material design as "his studies were not conceived as scalar models or representations of ideas; instead he identified the material behaviour itself as the driving force in an open-ended creative process".²⁹

Frei Otto, also known for material explorations, took a similar approach to material studies. While working on tensile structures Otto would perform 'form-finding' exercises with soap films.³⁰ The surfaces generated by the soap films were reflective of the properties and behaviours of the tensile materials Otto would use for his projects, such as the German pavilion at Expo 1967. This process of deriving form from material behaviour is described by Meissner as 'self-formation'.³¹

What is particularly interesting about both Josef Albers and Frei Otto's methods of material exploration is the manner in which they derive form from material behavior. This creates a 'bottom-up' technique similar to the approach

²⁸ Menges, Achim. *Material Synthesis: Fusing the Physical and the Computational*. London: Wiley, 2015. P.10

²⁹ Ibid., 9.

³⁰ Meissner, Irene, and Eberhard Möller. *Frei Otto: forschen, bauen, inspirieren / a life of research, construction and inspiration*. Edited by Cornelia Hellstern. First ed. Munich: Detail, Institut für internationale Architektur-Dokumentation GmbH & Co. KG, 2015. p.28

³¹ Ibid., 28

used by UNStudio in designing the Arnhem Central Station.³² This bottom-up approach, as opposed to top-down, considers the building components and materials as the foundation of the design, rather than coming up with a design and post-appropriating materiality. Furthermore, by developing form directly via innate material properties, direct feedback can be observed by changing the material qualities, the forces acting onto the material or the base parameters (such as anchor points). This 'bottom-up' approach will be applied to the working methodology for the digital mould as the materials (concrete and flexible membranes) will be informing many of the characteristics and limitations of the tool (the digital mould).

Fig. 18
Simulation emulating flexible membranes with differing tensile properties. The simulated panels membranes are created using an algorithmic script. Each panel has the same nine anchor points which determine the form of the simulated membrane.

³² Kestelie, Xavier De and Brady Peters. *Computation Works: The Building of Algorithmic Thought* AD. Hoboken, N.J.: Wiley, 2013. p.86

Fig. 19

This visual script correlates to the previous simulated membranes. Using a series of sliders and numerical values the script can be easily altered to simulate varying types of fabric and rubber like membranes.

2.7 - Tools //

The tool, is perhaps the last component of the fabrication process to be considered. Not to be forgotten or ignored, the tool plays a significant role as it determines many of the limitations and constraints of a construction process. Sennett's perception of the tool is that it acts as an integral part in the craftsman's development of skill. This development is not always derived by proper use of the tool, rather, Sennett argues that the craftsman is often challenged by tools which "are not fit-for-purpose".³³ These unfit tools urge the craftsman to use the tools in unconventional manners, even adapting the form of the tools to specific needs.³⁴ This adaptation of the tool forces the craftsman to fully understand the tool as it was, for all of its advantages and failings. It also ensures the craftsman's full understanding of the techniques at hand, before elaborating on the tool itself.

Through Sennett's lens, we can understand the tool as being potentially adjusted, even customized for a specific task. This view of the tool is not entirely new, take for instance the conception of Brunelleschi's design for the cupola of the Santa Maria del Fiore cathedral in Florence. In order to achieve this architectural feat Brunelleschi had to "design not only [the] structure but the machines and the process that enables its realization".³⁵ In this sense Brunelleschi redefined what was structurally feasible via the machines used for construction (the tools). This approach to tools may give greater plasticity to the other components within the design-fabrication process, as they are not confined by the particular limitations of the available tools.

³³ Sennett, Richard. *The Craftsman*. New Haven, London: Yale University Press, 2008. p.194

³⁴ *Ibid.*

³⁵ Picon, Antoine, and Alessandra Ponte. *Architecture and the sciences: exchanging metaphors*. New York, NY: Princeton Architectural Press, 2003. p.296

In *Architecture in the Digital Age*, Branko Kolarevic writes: “As constructability becomes a direct function of computability, the question is no longer whether a particular form is buildable, but what new instruments of practice are needed to take advantage of the opportunities opened up by the digital modes of production.”³⁶ In essence, Kolarevic calls for new tools and techniques to be developed in order to execute what is possible via digital means. This premise is essentially what this thesis aims to achieve.

Fig. 20
Sketches exploring ideas of constructing tools to locate the boundary of the panel on an uneven surface.

³⁶ Kolarevic, Branko, and Taylor & Francis Group. 2003. *Architecture in the digital age: Design and manufacturing*. New York: Spon Press. p.46

3.0 - Hybrid Technique //

3.1 - Hybrid manufacturing techniques

3.2 - Adjusting the digital design process

3.3 - Digital Mould, defining the tool

3.4 - Digital Mould, Prototype 01

3.5 - Digital Mould, Prototype 02

3.6 - Visual Lexicon of Panels

3.1 - Hybrid manufacturing techniques //

How may the previously mentioned digital and analogue design techniques coalesce to form a more cohesive digital-fabrication process rather than seeing the process as disparate elements? Through the use of algorithmic modeling techniques and the construction of the digital mould, this section will aim to answer this question by exploring what will be termed 'hybrid-techniques'. These hybrid-techniques will aim to inform the design-fabrication process from multiple parameters, such as construction constraints, waste generation, construction technique and material behavior.

Fig. 21

Sketch exploring ideas of how to map a grid onto the panel surface in parallel projection and potential substructure for panels.

3.2 - Adjusting the digital design process //

Fig. 22

The Images above illustrates a very simple algorithmic script (Grasshopper). The script takes a set of inputted points (five in this case) and interpolates a curve between them. Finally the script used this curve to create a dashed line with set dash and gap lengths.

Nodes and components:

- 01 - Input points
- 02 - Interpolate curve
- 03 - Dash pattern
- 04 - Two adjustable sliders corresponding to dash and gap lengths
- 05 - Merge data component

In order to create hybrid-techniques the digital design process must be approached from a slightly different perspective. Returning to previous points, the digital design process must remain open to reiteration while avoiding the ease of erasure Sennett criticizes in CAD processes.³⁷ Therefore, the digital framework must be open to quick change and input of new and variable parameters. For this reason, the CAD component of the process will be implemented as a visual scripting software known as Grasshopper. Grasshopper is an algorithmic modeling tool which acts as a plugin for the three-dimensional modeling software Rhinoceros.³⁸ Multiple factors make Grasshopper a suitable option to explore hybrid digital-analogue techniques. However, what is most desired from this software is its capacity to perform complex computational operations while providing an open environment for exploring digital design processes. Visual scripting as opposed to traditional scripting utilizes visual nodes which are symbolic of specific functions and operations.³⁹ By connecting these nodes and inputting desired parameters an algorithm can easily be created. This visual platform creates a more accessible and intuitive environment for scripting, enabling those with virtually no programming ability to generate scripts.⁴⁰

³⁷ Ibid., 41

³⁸ Tedeschi, Arturo, Fulvio Wirz, and Stefano Andreani. AAD, Algorithms-aided design: parametric strategies using Grasshopper. Brienza, Italy: Le Penseur Publisher, 2014. p.33

³⁹ Ibid., 27

⁴⁰ Ibid

3.3 – Digital mould, defining the tool //

The digital mould used in this thesis is akin to the flexible mould conceived by Lars Spuybroek in *Machining Architecture*. In principle a flexible mould would permit the re-positioning of one or more of its faces, enabling the same mould to be used to produce multiple varying products. In *Machining Architecture*, Lars Spuybroek writes about an adjustable mould comprised of splines which bend in two directions which he refers to as the 'flexi-mould' (see image below).⁴¹ Spuybroek explains that this device could be a means of creating double curved surfaces, ultimately marking a "shift from standardized pre-made elements to variable non-standard elements"⁴²

Fig. 23
Depiction of Lars Spuybroek's
flexi-mould concept.

⁴¹ Spuybroek, Lars. *Nox: Machining Architecture*. New York, NY: Thames & Hudson, 2004. p.164

⁴² *Ibid.*

3.4 – Digital mould prototype 01 //

Fig. 24
Digital Mould - Prototype 01 exploded axo illustrating the membrane surface, bed of pins (3x3) and the supporting frame.

The first iteration of the digital mould is comprised of four fixed faces which form a skirt and one adjustable face. The varying face is manipulated using a set of height adjustable pins which corresponds to a three by three grid of points, forming a low-resolution bed of pins. In order to create a surface between these pins, a flexible membrane is needed. In this case a 50 durometer, 1/32 inch silicon rubber sheet is used as the membrane surface. The mould itself is primarily constructed from 1/2 inch plywood, this enabled the components to be cut on the CNC mill ensuring a high level of accuracy between pins. Furthermore by digitally designing and CNC milling the components the mould can easily be replicated, fixed or adjusted if need be. The remaining components are comprised of typical hardware found at any local hardware store.

To accompany this digital mould a custom algorithmic script is developed in Grasshopper. Once a surface is inputted into the script the surface is automatically divided into 2' by 2' panels (correlating to the size of the mould surface). Once the surface is divided, the script then maps a 3 x 3 point grid onto each panel. This grid corresponds to a set of nine points which then get projected unto a common base plane. The distance between the original points and the projected points is then automatically listed .

Fig. 25
Surface which has been automatically panelized by the custom Grasshopper script.

Each panel then corresponds to a unique list of distances, spatially locating the nine points which will later define the surface. The following is an example of the list generated for panel #01 of the previously shown divided surface. The first number in the list corresponds to the point and the second to its height value in inches. The height value is calculated using the same base plane for each point. This base plane is set by the script to be located at the height of the point with the lowest Z value, meaning there is always one point in the list with a height value of 0. Subsequently, the height value of the other points in the panel are calculated as a difference in relation to this base plane.

Panel #01

0		0.0
1		3.3
2		6.2
3		1.2
4		2.8
5		4.0
6		6.2
7		4.7
8		3.5

Fig. 26
Image illustrating panel #01, the nine control points and their height value in relation to the base plane.

Fig. 27
Digital Mould - Prototype 01
Overall view

Fig. 28
Digital Mould - Prototype 01
View from below illustrating
height adjustable pins.

Fig. 29
Digital Mould - Prototype 01
View of fabric membrane
(mould surface)

Fig. 30
Digital Mould - Prototype 01
View of height adjustable
pins and locking mechanism

Fig. 31
View of mould surface
prepped with polyethylene film

For the first test panel, spray GFRc (glass fiber reinforced concrete) is explored as the medium applied to the flexible mould. For the first digital mould a silicon rubber membrane is used as the mould surface. Due to the wooden skirt, the mould must be covered with a thin low-density polyethylene film. This film serves two functions, first to prevent the concrete from bonding to the mould skirt and second to retain the semi-fluid concrete mix. In order for the concrete to be sprayed it is mixed to a semi-fluid consistency. The consistency is tested by dipping a concrete trowel into the mix. If the concrete falls off the trowel and leaves a 1/8" coating it has reached the correct consistency.

Fig. 32
First sprayed coat of concrete
(approx 1cm)

Once the concrete is adequately mixed and the proper consistency has been reached it is loaded into the hopper of the spray gun. The mould is then sprayed in even coats until a one centimeter layer has been achieved.

Fig. 33
Applying alkali resistive
fiber glass mesh to first coat

Once the first layer of concrete has been sprayed, an alkali resistant fiberglass mesh is placed on the wet concrete. The alkali resistive qualities of the fiber glass will prevent it from being corroded by the concrete overtime. For the mesh to follow the curvature of the mould it is cut into small triangular pieces.

Fig. 34
Complete layer alkali
resistive fiber glass mesh

Each piece of mesh is placed so that there is a slight overlap with the surrounding pieces to ensure proper cohesion. Additionally, the mesh is placed so that it remains approximately a half inch offset from the edge of the panel ensuring no pieces will protrude once it is demoulded.

Fig. 35
Applying second coat of sprayed concrete
(approx 1cm)

After the mesh has been placed, the second coat of concrete can be applied, once again spraying a layer approximately one centimeter thick.

Fig. 36
First GFRC test panel made with digital mould prototype 01.

Once the concrete panel was demoulded multiple unintended or unforeseen conditions were noticed:

- 1 - Edge condition is inconsistent
- 2 - Polyethylene film creates creases in concrete
- 3 - Membrane fasteners appears to be protruding through
- 4 - Silicon membrane appears to be buckling under load

These issues will be rectified by redesigning the digital mould to have slightly different properties. These differences will be covered in the following section: Digital Mould, prototype 02.

3.5 – Digital mould prototype 02 //

The second iteration of the digital mould is similar in principle to the first prototype, however there are a few key differences which aim to address the issues seen in the first test GFRC panel.

In order to rectify the panel edge condition, the skirt system is removed in the second prototype and replaced by a boarder which is placed directly onto the mould membrane. This boarder also enables greater control over the panel size, exterior profile and thickness, by adjusting the positioning and thickness of the boarder all of these parameters can be varied. The membrane surface is also exchanged for a 40 durometer, 1/16 inch neoprene sheet. This membrane provides more resistance in comparison to the silicone, in effect smoothing out the mould surface. Additionally, this digital mould has an increased pin-bed resolution, with a total of twenty-five pins. This should give the membrane added support, reducing the buckling effect seen in the first test panel. With the added pins the bed resolution has been doubled from the previous spacing of twelve inches between any given pin to six inches. Lastly, since the skirt system has been removed on the second prototype a new support system was designed. The new system acts as four separate legs which can easily be detached or replaced. This makes it easier to transport the digital mould and potentially change the height of the pin bed.

Fig. 37
Exploded axo view of digital mould
prototype 02

- 1 - Boarder
- 2 - Membrane
- 3 - Pin bed, total of 25 pins (5x5)
- 4- Detachable legs

Fig. 38
Digital mould, prototype 02 fully assembled

1 - Boarder strip [comprised of 1"x1/2" neoprene foam]	5 - Frame system which supports pins
2 - Membrane [2'x2' - 40 durometer, 1/16" neoprene sheet]	6 - Pin locking mechanism [1/4-20 Knobs]
3 - 1/4-20 connection with thread coupling	7 - Detachable legs
4 - Height adjustable pin	8 - Slot for ad-ons such as height adjustable feet

Required materials //

- (2) - 5'x5' -1/2" plywood sheets
- (75) - 1/4-20 UNC grade 2 hex nuts
- (25) - 1/4 x 1" UNC grade 2 cap screws
- (125) - 1/4 flat washers
- (25) - 3/8 x 5/8 x 1/4-20 barrel nuts
- (5) - 1/4-20 x 36" threaded rods
- (25) - 1/4-20 x 1 1/2" UNC grade 2 cap screws
- (25) - 1/4-20, female, three armed knobs
- (4) - #6x3/4" wood screws
- (1) - Bottle of wood glue
- (1) - 2'x2'x1/16", 40 durometer, neoprene sheet
- (1) - 1"x1/2"x25" neoprene foam strip role

In addition to the digital mould, a specialized tool needed to be designed in order to locate the corners of the panel. This tool will be referred to as the 'quad-point alignment gauge'. The gauge can be set to two preset panel sizes, 24" by 24" or 18" by 18". This gauge rests on the uneven mould surface, each post is carefully adjusted until the gauge is leveled, at which point it acts as a guide to place the boarder strips unto the mould surface. This guarantees that the panel will be 18" by 18" in parallel projection, ensuring continuity between panels.

Fig. 39
Quad point alignment gauge
(set to 18" x 18")

- 1 - Height adjustable post
- 2 - Spirit level
- 3 - Boarder strip (comprised of 1"x1/2" neoprene foam)
- 4 - Mould surface (membrane)

Fig. 40
Quad point alignment gauge
(set to 24" x 24")

Fig. 41
Digital mould component
CNC cut profiles layed
out on two 5'x5' sheets

Fig. 42
Digital mould components

Fig. 43
Digital mould assembled
(elevation view)

Fig. 44
Digital mould assembled
(elevation view rotated 45 degrees)

Fig. 45
Digital mould assembled
(detail view)

Fig. 46
Digital mould assembled with quad point alignment gauge

Fig. 47
Full final algorithmic panelization script
custom built for the digital mould.

01 /
This section of the script includes a series of input nodes for: the double curved surface, panel size, mould surface size and total number of pins in mould.

These values are used as inputs throughout the script to complete a series of operations.

02 /
This section uses the input surface to locate the corner of the surface. By locating the bottom right corner of the target surface, a reference point can be set. Additionally this section uses the mould surface size and number of pins to recreate the mould grid. This grid will later be arrayed and projected onto the target surface using the reference point as a starting position.

03 /
This section permits the mould grid to be arrayed based on the input values described in section 04.

04 /
This section provides the horizontal and vertical values for the panel array. These values can be changed using a slider accommodating different sized surfaces.

05 /
This section locates and numbers the panels situated on the target surface.

06 /
This section finds the point with the lowest x value for each panel and calculates the difference between the lowest point and the other points.

07 /
This section serves as a manual check of the maximum difference value for each panel. If any of the values exceed 8" (the limit of the mould pins in this case) the surface should be adjusted to ensure that none of the panels exceed the capabilities of the mould.

08 /
This section lists the high values for each panel. These values can be exported to an excel spread sheet and printed. These values serve as the inputs for the digital mould

Fig. 48
View of surface input into script.

Fig. 49 a
Close up view of final script. 1/2

Fig. 49 b
Close up view of final script. 2/2

Fig. 50

The image above illustrates the surface used as the input for the panelization script and the visualizations of the corresponding surface and grid generated by the script.

01 /
Original double curved surface modeled in Rhino.

02 /
Surface generated by Grasshopper fully panelized. Each panel is attributed a number and all 25 points are numbered.

03 /
Grid generated by panelization script. This grid is projected onto the double curved surface ensuring that the panels are 18"x18" in parallel projection.

04 /
Guides originally used to construct double curved surface.

Using the script illustrated in figure 47, a variety of double curved surfaces can be input to be automatically panelized. Once the surface is panelized the script will output a set of point values associated to each panel on that surface. Figure 50 illustrates the input surface used to generate a set of panels with the second iteration of the digital mould.

Using the mould //

Fig. 51
Locating the panel corners.

Fig. 52
Prepping the mould.

Fig. 53
Applying first spray layer.

The mould surface is prepped, first by setting the height value for all twenty five pins. Next, the quad point alignment jig is placed on the mould surface and leveled. Once the jig is level the rods are carefully aligned with the pins, situating the jig in the correct location. Plastic tubing is also added at this stage, these tubes will later be removed which will leave the panel perforated.

Once the jig has been set, the location of each corner is marked with a chalk line and the jig is removed. With the corners situated a strip of double-sided tape can be adhered to the mould surface. This will permit the neoprene foam boarder strips to be temporarily adhered to the mould surface. This foam boarder will define the edge of the concrete panel. For the first panel a bead of silicon is placed at all seams between the boarder strip and the mould surface in addition to each pin and vertical tube. A layer of painters tape is also added to cover the top surface of the foam strips.

Once the mould has been prepped, the GFRC (glass fiber reinforced concrete) can be applied. First, a 1/8" layer of concrete is sprayed evenly onto the mould. This spray application ensures a smooth and consistent finish on the concrete panel.

Fig. 54
Applying second layer.

The sprayed layer is then quickly brushed with a chip brush to remove any air bubbles and the next layer of concrete is applied. The second layer is mixed with loose 1/2" alkali resistant glass fibers. These fibers give the panel its strength and permit a thin application of concrete. In addition to the glass fibers a concrete admixture is added (Super six admix). The admix used contains: polymer, plasticizer, shrinkage reducer, de-foaming agent, wetting agent and a water proofing agent. This mixture of concrete is applied to the mould by hand and evenly spread across the surface.

Fig. 55
Finishing pass.

Once the second layer has been applied the excess concrete must be removed. A trowel is used to scrape the excess concrete from the edge of the panel, the foam border strips are used as a guide for the trowel. This ensures that the edge of the panel is 1/2" thick. Excess concrete is also removed from the tubing ensuring ease of removal once the panel is demoulded.

Fig. 56
Finishing pass closeup.

Fig. 57
Curing process.

Finally, the panel cures for a minimum of 24 hours before it is removed. A thin low-density polyethylene film is placed over the mould, this will prevent the water in the concrete from evaporating too rapidly. Furthermore, the film helps to trap some of the heat generated by the curing concrete, in turn accelerating the curing process.

Fig. 58
Demoulding panel, foam strip closeup.

Once the panel has cured, the film, tape, tubing and foam border strips are removed. The foam boarder strips are peeled and reused for the next panel. The tubes can also be reused if the cured concrete residue has been removed from them. Before the mould is reused, it is quickly scrubbed to clean the neoprene membrane and remove any residual concrete and silicone debris.

Fig. 59
Vials of material samples.

- 01 /**
Alkali resistant fiberglass scrim mesh
- 02 /**
Alkali resistant 1/2" fiberglass loose fibers.
- 03 /**
Tap water
- 04 /**
Super Six Admix (for self consolidating ultra high performance concrete)
- 05 /**
Portland type 1 concrete.

In order to fabricate 18"x18"x1/2" GFRC panels the materials shown in figure 59 were combined in the following proportions:

Spary mix //

- 70g of Super Six Admix
- 2.2 Kg of Portland type 1 concrete
- 750ml of water

Backer mix //

- 180g of Super Six Admix
- 3.6Kg of Portland type 1 concrete
- 1L of water
- 155g of Alkali resistant glass fiber

Fig. 60
Panel 01, test of second digital mould. Side and top view.

Using the second iteration of the digital mould three concrete panels were constructed. The first of these panels was a test of the maximum possible deflection between pins. This panel serves the purpose of illustrating the maximum curvature considering the qualities and constraints of the mould such as the elasticity of the neoprene membrane, size of panel and pin adjustment limitations (see figure 60).

Fig. 61
Panel 02, test of panelization script. Side and top view.

The two other panels served the purpose of testing the panelization script (see figure 47). These panels test whether the script is properly describing the surface, ultimately permitting a larger surface to be constructed using the digital mould (see figures 61 and 62). Furthermore, these panels illustrate the different quality of panel produced by the second iteration of the digital mould.

Fig. 62
Panel 03, test of panelization script. Side and top view.

Fig. 63
Panel 02, test of panelization script. Side
and top view (closeup).

If the panels made using the second iteration of the digital mould are compared to the test panel in figure 36, it becomes evident that all of the inconsistencies and defects have been rectified or addressed in some manner.

- 1 - Edge condition fairly consistent due to panel border strips
- 2 - Panel surface is smooth due to removal of film.
- 3 - Panel perforations become intentional as a means to fasten the panels or as an aesthetic element.
- 4 - Membrane buckling is rectified by increasing the pin resolution and membrane thickness.

Fig. 64

Two panels made using the panelization script, describing a larger surface.

The corresponding points for both panels are listed below:

Panel 01 //	Panel 02 //
01 - 6.5	01 - 8.0
02 - 6.75	02 - 6.5
03 - 6.5	03 - 4.75
04 - 5.5	04 - 3.25
05 - 4.0	05 - 2.5
06 - 6.0	06 - 7.0
07 - 6.25	07 - 5.25
08 - 5.75	08 - 3.5
09 - 4.5	09 - 2.25
10 - 2.75	10 - 1.5
11 - 5.25	11 - 5.75
12 - 5.25	12 - 4.0
13 - 4.5	13 - 2.25
14 - 3.25	14 - 1.0
15 - 1.5	15 - 0.5
16 - 4.0	16 - 4.75
17 - 4.0	17 - 3.0
18 - 3.5	18 - 1.5
19 - 2.25	19 - 0.25
20 - 0.5	20 - 0.0
21 - 2.75	21 - 4.0
22 - 2.75	22 - 2.5
23 - 2.25	23 - 1.25
24 - 1.5	24 - 0.25
25 - 0.0	25 - 0.0

The image above illustrates the two panels made using the panelization script. Once these panels are placed next to each other it become clear how they start to describe the larger input surface illustrated in figure 50. These panels illustrate that using the panelization script and the digital mould, a custom double curved facade could be constructed, despite each panel having to be unique.

3.6 – Visual Lexicon of Panels //

In addition to the panelization script, a secondary grasshopper script was built to help illustrate the potential of the digital mould. This secondary script generates a panel for the digital mould using random values for the point heights. These random values are created using a component which generates a random list of values within a range of 0" to 8". The particular values are defined by a seed number, this seed number essentially acts as a unique identification number for each randomly generated panel. The output for this script is illustrated below in figure 65.

Fig. 65

Sample of a panel generated by Visual Lexicon of Panels script.

01 /

This number corresponds to the panel seed number. By inputting this seed number into this script this particular panel can be replicated.

02 /

This number corresponds to the identity of one of the 25 pins in the digital mould.

03 /

This number indicates the height value of each individual pin.

04 /

This line indicates the location of the 18"x18" panel boarder.

05 /

This surface represents the mould surface (2'x2').

Fig. 66
Visual Lexicon of Panels script.

01 /

This node serves as the input for the 25 points which make up the mould grid.

02 /

This section finds the first and last point in the list and created a bounding box around the grid of points. This is later used to define the panel boundary.

03 /

This section attributes a random z value for each point between zero and eight inches (0-8"). These random values are created using an input seed value. Each seed value corresponds to a particular set of point locations which can be repeated by inputting the original seed value.

04 /

This section moves each point by the z value which was designated to it.

05 /

This section list the seed value in model space for user reference.

06 /

This section creates a surface with the moved points. Furthermore, there is the option of interpolating between points to create a smoother surface, which is more reflective of the properties of the digital mould.

07 /

This section reconstructs the surface mentioned in section 06 as a mesh. This permits the surface to be colored later on.

08 /

This section created a domain of the smallest and largest z values in each panel.

09 /

This section colorizes the mesh described in section 07 according to the domain constructed in section 08.

10 /

This section uses the domain constructed in section 08 in conjunction with the grasshopper component called 'Galapagos' to test for a specific z value differential. Once the user sets the desired panel differential, Galapagos will automatically search through the possible seeds to find a panel with the nearest differential to the one set by the user.

11/

Feedback loop between Galapagos component and seed value.

Fig. 67 a
Visual Lexicon of Panels script close up
view.

Fig. 68
Sample of panels nearest to target value of 5" difference between lowest and highest points.

Using the Visual Lexicon of Panels script tens of thousands of unique panels can be generated and exported. To illustrate this point the first two hundred seeds have been exported and listed in Appendix A.

In addition to randomly generating panels, the Visual Lexicon of Panels script contains a grasshopper component called 'Galapagos'. Using Galapagos the script can analyze each panel based on a specific value. In it's current configuration, the script uses Galapagos to search for a specific value corresponding to the difference between the lowest and highest points on the panel. If this value is set to five inches, Galapagos will search through the seed values and list the panels which best fit this target value. In effect creating a feedback loop between the current panel data and the set seed value. Figure 68 demonstrates three panels generated by the script which all match the set target value of five inches (5") within a tolerance of 0.1 inches. With some manipulation of the script the target value could be changed to any given value intended by the designer. The script could also be adapted to manipulate the input surface rather than separate panels.

4.0 - Conclusion //

4.1 - Terminus

Terminus //

How can complex computer aided design processes be better implemented by thinking of the design-fabrication process as a whole rather than as separate practices?

What is perhaps most significant about this thesis, is the understanding of the design to manufacturing process as being imperfect. Much like Sennett's understanding of the craftsman's relationship to his tools; the design to fabrication process is adaptable. Once the craftsman understands the limitations of his tools he can elaborate and adjust the tool to suit his needs. In this case, the Digital Mould is a culmination of techniques, analogue and digital, design and fabrication based. In this sense, the Digital Mould embodies a series of 'adaptations' leading up to a final design intention: to construct a digitally informed double curved concrete surface. The steps taken to achieve this design intention are informed greatly by the research and literature elaborated in the chapter 'techniques'. Furthermore, each step or decision serves a specific task in achieving this design intention. Glass fiber reinforced concrete is carefully chosen as it enables a thin, strong and durable panel to be made in a relatively affordable and available additive manner. Grasshopper is chosen as the means to digitally design the double curved surface as it permits computation to be leveraged in calculating the innumerable values associated to each panel; ultimately translating these values into a tangible list of lengths. Additionally, the nature of algorithmic scripts allows the surface and associated parameters to be changed quite easily. Moreover, using the script, a variety of surfaces can be input and automatically converted into a set of instructions for the

mould, facilitating the computational aspect of this process. Lastly, the mould components are intentionally CNC milled to maintain a high degree of accuracy while ensuring that the mould can easily be replicated, expanded, adjusted or repaired. It is the culmination of these decisions which lead to 'new instruments of practice' as Kolarevic established⁴³. In essence, the digital mould acts as a new tool and technique for fabricating a specific design intention.

What makes this particular tool unique is its open framework and DIY (do it yourself) qualities. In contrast to most digital fabrication tools available to designers (laser cutters, CNC mills, 3D printers) the digital mould presented in this thesis is intentionally built with an open framework in mind. Every facet of the project lends itself to a DIY process. The digital component, Grasshopper, is a free software available to anyone who has a copy of Rhinoceros. Furthermore, the scripts could easily be published on the online Grasshopper forums, making it accessible and editable. Lastly, the three dimensional model and two dimensional cut files of the digital mould could be published online as well, permitting anyone with the capability to do so, to edit, expand or simply duplicated the design. In essence, anyone with access to a makerspace or a CNC, a hardware store, and a computer could build their own version of the digital mould for a relatively low cost of approximately three hundred and fifty dollars (This amount is based on the size and configuration of the digital mould presented in this thesis). This opens up the realm of digital fabrication methods allotted to students, designers and architects and gives them direct control over the tool and its corresponding 'software' (Grasshopper scripts). This DIY quality

⁴³ Kolarevic, Branko, and Taylor & Francis Group. 2003. *Architecture in the digital age: Design and manufacturing*. New York: Spon Press. p.46

permits the digital mould to be altered according to a particular design or intended material application. In essence opening up a tangible realm of exploration and customization within digital-fabrication to a wide range of designer and makers.

The research conducted in this thesis serves as a starting point for open-source experimentation with digitally informed flexible-moulds. In this project the applied material was glass fiber reinforced concrete, however in future research or use of the mould other material alternatives could be explored. Other areas of research could also involve alternatives for the mould membrane, different mould sizes and varying pin bed resolutions. Simultaneously the research could also involve the alteration of the script to suit these new qualities or attempt to optimize the current use of the mould. Through discussion of the project, Maria Mongallon suggested that in the future, the panelization script could be altered so that instead of panelizing the surface according to a regular pattern, it could be panelized so that the seams fall on the areas of the surface with the least curvature. Ultimately, this would reduce harsh transitions between panels. This point serves as a good example of how the scripts could be further developed and improved to suit a particular application of the digital mould. Furthermore, this point showcases the appeal of this method of digital-fabrication; it's open framework and customizable nature.

Throughout the thesis the concept of feedback is contemplated as a possible component of the design-fabrication process. However, it is not until the end of the thesis that this idea is explored with the Visual Lexicon of Panels script. This script begins to investigate the concept of informing the panels using a target value specified by the designer,

permitting the designer to explore variations of the panel within a specified range of curvature or deformation. Later it is speculated that this approach could be also used to inform the larger surface as a whole with some manipulation of the script. Additionally, through critical review of the thesis, concepts of informing the scripts based on feedback loops between the mould (material properties) and some form of metric (force exerted on each pin, deformation of mould surface, etc.) were brought up. This form of feedback is beyond the scope of this particular thesis, but could be an area of continued research as a means of improving the manufacturing technique and more closely linking the design process to the tool (mould).

It should be noted, that there is a secondary form of feedback involved in the process of iteratively designing a custom fabrication tool (digital mould in this case). This secondary form of feedback is not pure in the way of the digital feedback present in the Visual Lexicon of Panels script, rather it is a feedback mediated by the designer. Through simultaneously understanding the design process and the technique, the designer can return to the beginning of the design-fabrication process, altering it based on the information gained from the previous iterations. This process can be seen in the redesign of the second version of the digital mould. Through building the first version of the mould, information pertaining to the material qualities of GFRC could be noted and used to improve not only the design of the mould but potentially the design of the script as well. This example returns to the point of the craftsman's responsibility, or perhaps in this case the responsibility of the designer or architect, to compensate for the inaccuracies in the work; to reiterate on the tool until it suits the needs of the designer.

In summary, the digital mould does not necessarily perform a new task, but rather it enables a new method of performing that task. There are current methods of constructing double curved concrete panels (such as CNC milling moulds). However, what it does permit, is an accessible means of digital fabrication. With its open framework and ease of producibility the digital mould brings digital fabrication to a realm which is tangible for designers, students, architects and makers. This accessibility could facilitate the progression and exploration of design-fabrication work flows and further the use of bespoke designs within architectural contexts. The digital mould presented in this thesis does not directly reshape the landscape of architecture, but rather the means of acting within that landscape and perhaps the degree to which people act within it.

Appendix A - Visual Lexicon of Panels //

This lexicon illustrates the first 200 seeds for the randomly generated panels. These 200 unique panels only represent a minuscule fraction of the unique panels that can be created using the digital mould.

Glossary //

Acronyms --

AAD / Algorithm Aided Design⁴⁴

CAD / Computer Aided Design⁴⁵

CAM / Computer Aided Manufacturing⁴⁶

CNC / Computer Numerical Control⁴⁷

GFRC / Glass fiber reinforced concrete

Key terms --

Algorithm /

"A procedure used to return a solution to a question – or to perform a particular task – through a finite list of basic and well-defined instructions."⁴⁸

Analogue /

"Of signals or data: represented by a continuously variable physical quantity, such as voltage, spatial position, etc."⁴⁹

Craft /

"To make or construct skilfully."⁵⁰

⁴⁴ Tedeschi, Arturo, Fulvio Wirz, and Stefano Andreani. AAD, Algorithms-aided design: parametric strategies using Grasshopper. Brienza, Italy: Le Penseur Publisher, 2014.

⁴⁵ Dunn, Nick. Digital Fabrication in Architecture. London: Laurence King Publishing, 2012. p.186

⁴⁶ Ibid.

⁴⁷ Kolarevic, Branko, and Taylor & Francis Group. 2003. Architecture in the digital age: Design and manufacturing. New York: Spon Press. p.15

⁴⁸ Tedeschi, Arturo, Fulvio Wirz, and Stefano Andreani. AAD, Algorithms-aided design: parametric strategies using Grasshopper. Brienza, Italy: Le Penseur Publisher, 2014. p.22

⁴⁹ "Analogue, B.n.1, c". OED Online. March 2017. Oxford University Press. <http://www.oed.com.proxy.library.carleton.ca/view/Entry/7029?redirectedFrom=analogue#eid> (accessed March 29, 2017).

⁵⁰ "Craft, n.2". OED Online. March 2017. Oxford University Press. <http://www.oed.com.proxy.library.carleton.ca/view/Entry/43695?rskey=8MG8MR&result=2&isAdvanced=false#eid> (accessed March 29, 2017).

Feedback /

The modification or control of a process or system by its results or effects

Logic /

A system or set of principles underlying the arrangements of elements in a computer or electronic device so as to perform a specified task.

Parameter /

A quantity whose value is selected for the particular circumstances and in relation to which other variable quantities may be expressed.

Parametrics /

"Parametrics can provide for a powerful conception of architectural form by describing a range of possibilities, replacing in the process stable with variable, singularity with multiplicity."⁵¹

⁵¹ Kolarevic, Branko, and Taylor & Francis Group. 2003. *Architecture in the digital age: Design and manufacturing*. New York: Spon Press. p.17

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Figures //

Figure 08 : One Main Office Renovation

"One Main Office Renovation / dECOi Architects" 21 Dec 2015. ArchDaily. Accessed 7 Jan 2017. [←http://www.archdaily.com/778976/one-main-office-renovation-decoi-architects/→](http://www.archdaily.com/778976/one-main-office-renovation-decoi-architects/)

Figure 09 : Minibuilders - completed form

"Minibuilders." Institute for Advanced Architecture of Catalonia. Accessed March 30, 2017. <https://iaac.net/research-projects/large-scale-3d-printing/minibuilders/>.

Figure 10 : Minibuilders - progress

"Minibuilders." Institute for Advanced Architecture of Catalonia. Accessed March 31, 2017. <http://robots.iaac.net/#robots>

Figure 11 : Aerial view of Arnhem Central Station

Karissa Rosenfield. "Gallery: UNStudio's Arnhem Transfer Terminal Through the Lens of Hufton+Crow" 16 Dec 2015. ArchDaily. Accessed 8 Jan 2017. [←http://www.archdaily.com/778950/gallery-unstudios-arnhem-central-station-through-the-lens-of-hufton-plus-crow/→](http://www.archdaily.com/778950/gallery-unstudios-arnhem-central-station-through-the-lens-of-hufton-plus-crow/)

Figure 12 : Bespoke panel profiles

Kestelie, Xavier De and Brady Peters. Computation Works: The Building of Algorithmic Thought AD. Hoboken, N.J.: Wiley, 2013. p.87

Figure 16 : Josef Albers and an exploitative paper model

Menges, Achim. Material Synthesis: Fusing the Physical and the Computational. London: Wiley, 2015. p.9

Figure 17 : Frei Otto soap bubble experiments

Meissner, Irene, and Eberhard Möller. Frei Otto: forschen, bauen, inspirieren / a life of research, construction and inspiration. Edited by Cornelia Hellstern. First ed. Munich: Detail, Institut für internationale Architektur-Dokumentation GmbH & Co. KG, 2015. p.39

Figure 23 : Lars Spuybroek's flexi-mould concept

Spuybroek, Lars. Nox: Machining Architecture. New York, NY: Thames & Hudson, 2004. p.164

Note: All other figures and images included in this document are of my own work.