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FORM FOLLOWS PARAMETERS

Parametric modelling for fabrication and manufacturing processes

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

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

1. Introduction

The authors began their exploration by questioning how parametric modelling influences the manufacturing process. During this exploration an architectural research project named Protocol began to emerge. In this project, the authors investigate how the manufacturing of plastics (casted, extruded, 3D printed and rotor-moulded) can be incorporated in the design and fabrication of temporary structures. The framework of this structure is developed though a parametric script which manifests itself through the input of points. These points were studied in terms of the connectivity and relationships to one another, resulting in an architectural framework that resembles a triangulated pattern. The authors chose to work with triangulated geometries because of the ability to link the input parameters to each other and explore the spatial relationships at the simplest geometric level. The wireframe of the triangulated structure marks the dimensional qualities of each controlling point and its influence on the designed space.

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

2. Project development

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

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

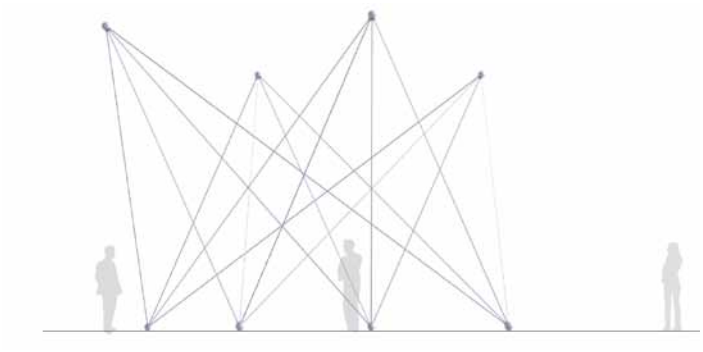

Figure 1: Protocol structure framework without skin

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

2.1. THEORECTICAL FRAMEWORK

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

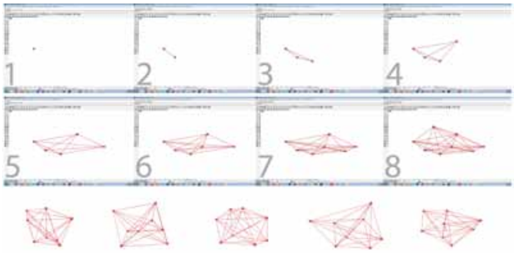

Figure 2: Grasshopper definition and parametric control of fabrication parameters

3. Industrial manufacturing in architecture

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

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

4. Control of parametric design

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

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

4.1. PARAMETRIC CONTROL OF FABRICATION

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

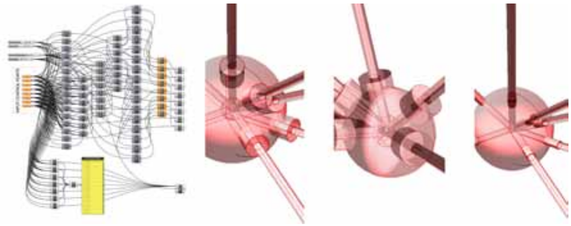

Figure 3: Plastic extrusion process

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

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

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

4.2 CHOOSING 3D PRINTING AND MOULD MAKING

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

Figure 4: Mould making and casting process

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

5. Exploration of industrial manufacturing

5.1 INTEGRATION OF PLASTIC EXTRUSION

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

Figure 5: Temporary shelter using connection joint and industrial manufacturing

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

5.2 INTEGRATION OF MOLD MAKING AND CASTING

Mould making and casting techniques were simulated with the intent of them being able to be mass manufactured (Figure 6). The 3D printed connection joints were used as the initial form in developing a two-part mother mould. The mother mould was poured from a silicon rubber that has a high durability and life expectancy. Because the 3D printed connection joints have a series of undercuts within the design it was important to use Dragon Skin silicon rubber or similar silicon product for its durable nature and high levels of elasticity. The process of making a two part mould is a common practice in industrial manufacturing processes. This type of mould can be used to produce hundreds of casted parts without losing quality in the final product.

Figure 6: Mould making and casting process

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

6. Conclusion

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

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

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

Figure 7: Temporary shelter using connection joint and industrial manufacturing

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

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