Interactive Information Model for Digital Fabricator

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Abstract

This paper describes the research of parametric and procedural modeling techniques associated with digital fabrication and form-finding within architectural design. The outcome of this design procedure surpasses traditional views of an optimized single solution that travels down a linear pipeline – architect, engineer, contractor and fabricator - to seek approval from various design professionals before fabrication begins. Instead, this approach offers an interactive information model which contains parameters that perform actions based on the specialization of various design professionals. Within a parametric field, the information model instantly acknowledges any errors in the design or fabrication process. The quantity of these interchangeable parameters is proportional to the number of constraints and regulations that the actors and the building must meet. This model can be easily unfolded into an open-end non-linear design loop that manifests optimized solutions which are achievable in a "file-to-factory" scheme. This new approach of using non-linear procedural modeling to generate parametrically negotiable solutions across various design professions are explored in two experimental projects that are described in the paper. With the procedural modeling of the MathMorph project, a large quantity of spatial arrangement solutions grew out of a fixed set of parameters defined by mathematical equations. Randomness, noise, permutation and recursion were introduced into the form seeking and fabrication process that yielded novel design solutions represented both digitally and physically. With laser cutting technology, Swell_Fab.Lab project, a digital prototype of a parametric information model was generated to simulate all aspects of surface properties before fabrication and installation.

1. Non-linear Interactive Approaches in Information Modeling

Traditionally, the design process of the architectural industry utilizes a linear approach to incorporate various actors into a design/build system. The system breakdown of actors begins with the architect who then interacts with the owner and consultants. After the architect completes the design and construction document as a part of legal document, are then mainstreamed after bid to the general contractors. Then the general contractors and sub contractors are responsible for completing the construction and ultimately deliver the building to the owner. This linear process does not encourage an interdisciplinary collaboration to evolve. In the bidding process, it is common for a contractor to take the design as a finished product without negotiate or propose alternative solutions (fig. 1: top). This separation eventually results in a high cost to correct any early design issues in the later construction phase. "Without a broader system, the drive for form has been listless, lost in self-referential exercises, meaningless outside the field of architecture itself. Instead, architecture should perform rather than simply form; structurally, environmentally, economically, programmatically, contextually, or in multiple formal arenas.” (Meredith 2008).

By investigating a non-linear approach to building information modeling (BIM), the model manifests into a parametric system that is controlled by various professionals. Many early design and fabrication issues can be solved by capitalizing on the dynamic interaction between the designer and fabricator. The evaluation of the information model depends partly on the feasibility of a form, based on if it satisfies the functions and conditions within the actors’ profession, and partly on its aesthetic value, which is subject to all reviewers.

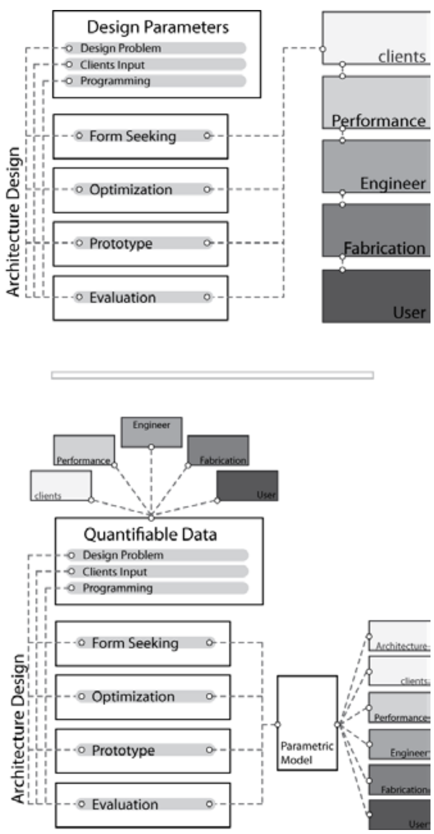

Figure 1: Top: Traditional workflow in AEC. Bottom: Non-linear Information Model

A non-linear approach (fig. 1: bottom) is optimized by the processing of configured components that are developed by each of the actors. The quantity of these interchangeable parameters is proportional to the number of constraints and regulations that the actors and the building must meet. The information model is developed by combining these components into one parametric system that seeks form and fabrication. This dynamic process surpasses traditional linear approach to design and build by looking at the power of collaboration to drive the information modeling.

2. Non-Linear Modeling – Form Finding

The use of various modeling programs, from procedural modeling tools such as Grasshopper for Rhino and Houdini to algorithm and equation driven modeling in Mathmatica and Mel Script, allow for several design and fabrication components to act parametrically with one another. Exploring the parametric computing and fabrication techniques, with the emphasis on the potential of fabricating forms, is a complex and dynamic way to produce architectural novelty and originality. An architectural form grows into a synthetic information model, which exists for a meaning far beyond aesthetic values. Within these modeling programs, several variations of form-finding emerge. Each of the form-finding techniques can be either used independently or in combination of another.

2.1. Panelization + Tessellation

Panelization or tessellation, as a form-finder, is a generation of division points upon a surface. Once the points have been defined, the surface is populated with a new set of connecting geometries that have no overlapping elements or an absent of surface elements, this processes leaves a faceted surface that is determined on the amount of division points that are generated. A known or unknown pattern can be developed from panelizing or tessellating a surface. The panelization and tessellation can be parametrically controlled through surface manipulators that allow variable changes in terms of the division of points. A surface can have an increasing level of complexity, by either panelizing or tessellated, that fluidly enhances the curvature by dividing the surface into smaller segments. This division of a surface can take the form of many different geometric or organic patterns. Different algorithms can be applied to the surface in order to change the tessellation. Through this form-finding method, highly complex surfaces can be easily constructed by breaking apart the connected geometries. The individuality of each pattern may be fabricated and labeled through digital fabrication.

Algorithms and codes can parametrically control the individual surfaces and prepare them for fabrication, while simultaneously placing limitations on the design due to structural constraints. “Digital technologies have revitalized the design world’s interest in patterning and tessellation because they afford greater variation and modulation through nonstandard manufacturing, even as they provide an inherent economy of means. Working digitally enables movement from one representational format to another – for example, from digital model to vector-line file to manufacturing method.

This series of translations allows for a more fluid fabrication process while significantly reducing the labor associated with taking one type of design medium and turning it into another.” (Iwamoto, 2009). An example of the fabrication preparation would be a tab system that can be added to each of the panels. The tabs would allow for the panels to be connected by folding them to an appropriate angle in order to meet the neighboring panels (fig. 2). This fabrication method also allows for an individual to realize a new pattern that emerges from the tabs being folded about an axis on the individual panels. When utilizing a tab design several components are able to be parametrically controlled. The tab offset distance and the angle of the tab ends can be controlled to meet a user’s desirer.

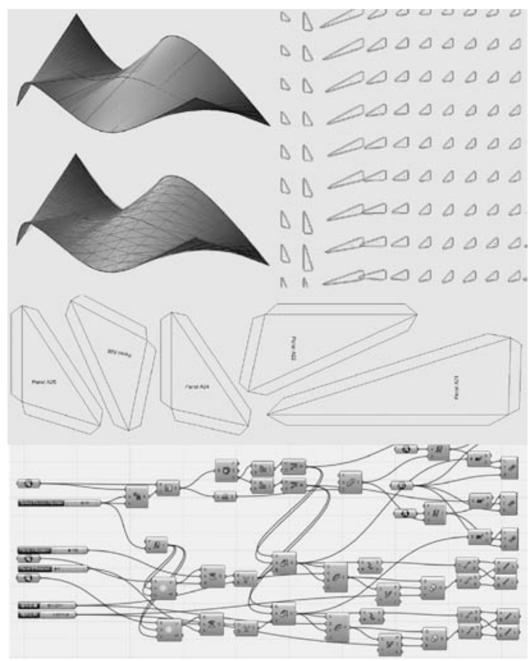

Figure 2: Panelization of surface showing tab system and cut diagram – script built to input any surface

2.2. Permutation

Permutation, as a form finder, is explored by defining a node network and variables with digital models. By generating a node network, the information modeler allows for a mapping or cross-referencing process to evolve within a single information model. Permutation is a computational approach that defines the relationships between nodes in the network with other nodes in the same network. This algorithm allows for form-finding to output several generations that are considered to be an offspring of one another. For example: In the pursuit of finding form, a user may be inspired by the genetic algorithm that simulates the reproduction of biological organisms. By using a non-linear information model, one is able to combine and merge existing forms / solutions to generate new solutions with inheriting features. In another words, the population of the new solutions is "built up" by "mixing" the gene of survivors. The specific characteristics of each offspring forms are inherited from both parent forms through their control nodes. Each node's spatial value carried in parent forms is passed to their children's related node with a randomly assigned weight. For instance, various program and scripts were utilized to create the first generation of the following roof surfaces (Fig. 3). A prototype matrix was created to drive the deformation of target geometry mesh. A large quantity of the "children" roof surfaces was produced from each pair of "roof" parents. The first child was identical to parent-A, while the last child was identical to parent-B. Other children were just the mixture of parent A and B with a different weight combination.

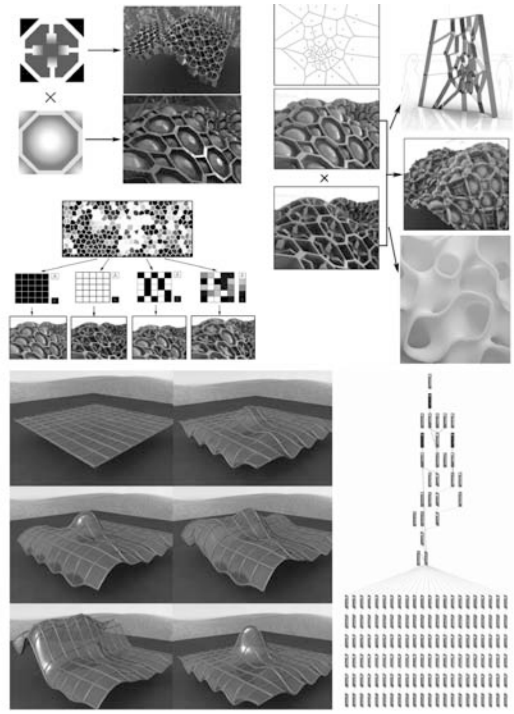

Figure 3: various projects completed by authors using permutation in several non-linear models

One can apply this method to "breed" forms across several generations. Generating several generations of forms is possible because of the parametric control over the number of elements input into the system. For example, several ideal roofs were selected from the second generation based on aesthetics and reviewers' criteria. These "survivors" then blended with each other again and generated the third generation.

While the forms are being generated, the algorithm is also relying on the fabrication process component to eliminate the solutions that cannot be fabricated due to the constraints that are inputted. This form finding method allows for a non-linear information modeling process to work parametrically and remain selective in its outputs.

2.3. Controlling Form Logic through Math

Generative form finding frequently takes the inspiration of the geometric aesthetic of mathematic forms. Experimentation in mathematics, 3D algebra and 4D (3D + time), can yield new forms for fabrication and assembling. New solutions are either adapted to fused deposition modeling (FDM) or laser cutting fabrication pipelines that integrate within the non-linear information model. In this strategy, some math calculations such as random noise, sine and cosine are introduced into the procedural model. The noise normally has a subtle effect on the final form unless it is amplified. The result, or the noise accumulated, allows for several computation cycles to be output. This type of mutation allows the complexity of a form to grow continuously as long as the computation proceeds.

In 1998, Roxy Paine explored the generative form-finding processes of math in his *Auto Sculpture Maker* (SCUMAK).[i] In his installation, Paine used a computer controlled machine to create polyethylene sculptures. Each sculpture was formed by rigidly scripted data and produced with identical parameters. However, due to the forces of chaos, the produced forms were all different. Roxy Paine created the contrast between his personalized mass production and the depersonalized industry manufacture pipeline. Here, mathematic equations were used to massively manifest a large quantity of 3D forms very rapidly and effectively. These equations could be used to generate forms by looking at a chaos method or introducing a level of randomness into the procedural model (fig 4).

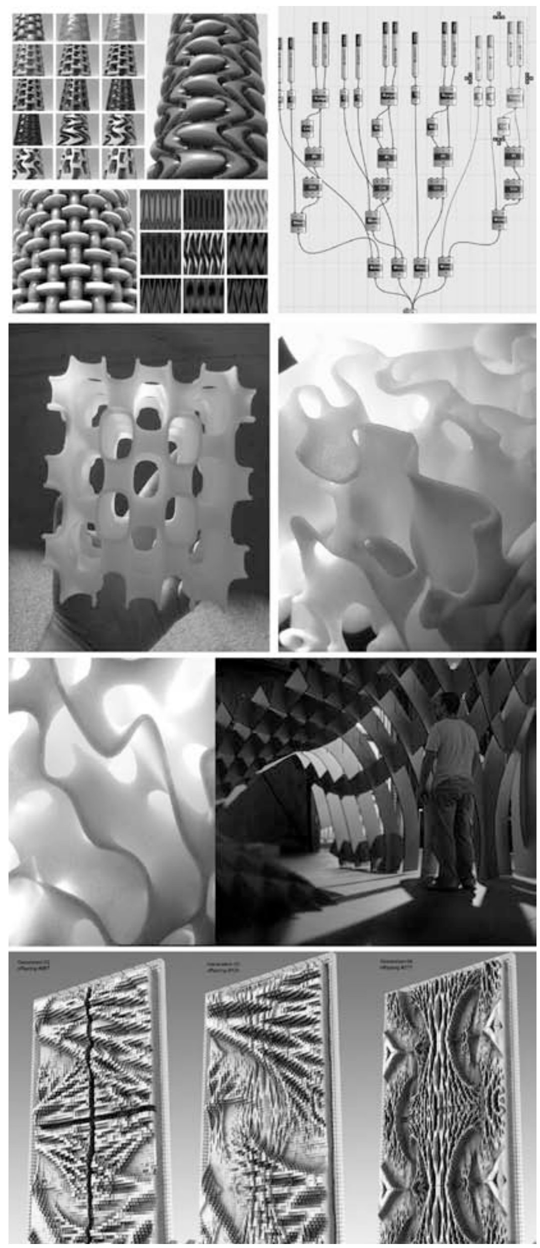

Figure 4: various projects of authors completed with mathematic parameters

While using a non-linear information model, the user would be able to instantaneously output diagrams and models needed to fabricate. Here, the fabrication actor is needed to integrate a different form of mathematical data. This data can range from material size, machining limits, to cutting tool sizes and tolerances. All these raw data can be viewed as a logic that places limitations onto a mathematically driven form.

3. Digital Fabrication as an Integrated Entity

Digital fabrication is the static manifestation of the dynamic digital world. The architectural field is realizing the potential of digital technologies that can further the current construction processes of artifacts. Digital fabrication serves as the linking entity between the architect and the manufacture processes of “file-to-factory”. “The close relationship that once existed between architecture and construction (what was once the very nature of architectural practice) could potentially reemerge as an unintended but fortunate outcome of the new digital processes of production.” (Kolarevic, 2003) By utilizing digital fabrication as an integral entity in the design process, the architect has the ability to design parametrically with instantly knowing the limitations of the current manufacturing technologies, “therefore, digital fabrication technologies introduce a number of realistic considerations into a digital-design process; nevertheless these constraints bound the range of design possibilities but in the same time they provide tangible and generic means for design actualization.” (Dritsas, 2002).

The marriage between the digital world and fabrication needs to have a seamless transition that allows designers not to have to learn the language of computing but utilize the tools presented by manufactures.

3.1. A New Modeling Procedure

Digital fabrication is made possible by the transferring of g-code – computing language - from a digital model to the fabrication machine. The introduction of these new manufacturing processes into the architecture field has allowed for a new craft of model building to emerge. Today, it is possible for the architect to manifest their designs at a micro scale that has the same precision of the fabrication industries’ full scale construction. The gap between the digital and the physical realm is narrowing due to the design practice having an increased accessibility to CNC mills, laser cutters and FDM printers.

The design process can greatly benefit from learning how to utilize these digital fabrication processes such as CNC, laser cutting, water-jetting or milling machines. These fabrication processes favor models to be investigated by either paneling or serial study techniques. These techniques can be used to manifest a model that portrays far more information than the architectural models of the past. Laser cutting and CNC milling utilize a subtractive process of material in order to manifest the artifact. Fused deposition modeling allows for artifacts to be grown in a serial process that acts in an additive process of materials. The benefit of FDM fabrication is having the ability to generate fluid models that are impossible to manifest utilizing traditional hand making modeling techniques. Due to the advancement of digital technologies, architecture models now represent more than the typical volume, scale, void or programmatic diagrams.

Using precision of digital fabrication to produce models allows for more information to be examined in physical model format – wind testing, structure and responsive performance. This new modeling procedure has worked as a digital learning tool for the construction processes and also serves as an efficient way to transfer construction documents into full scaled manufactured parts.

3.2. Scalability – Exploration of Micro to Macro

Digital fabrication has given architecture the tools needed to manifest the conceptual ideas into the built environment. Architects must understand the importance of the digital fabrication machines minimum and maximum allowances. Part of the design challenge, when designing with digital fabrication as a component in the information model, is to be able to realize the conceptual idea with the allowance of the current fabrication tools such as laser cutter and CNC mills. “Designing manufactures allows us to posit an investigation of the exhibitive act of architecture and of its processes within the framework…” (Costa 2003). The massive scale of architecture trumps the micro scale of most digital fabrication machines.

Over the past several years, designers have showcased the ways to build from a micro scale and produce the macro scale. By exploring the ways in which the designer can utilize the current fabrication machines, to produce at a macro scale, will inevitably progress the current construction processes and allow for digital fabrication to be an integrated component into the design process. As the architecture field continues to exploit these digital fabrication technologies, the only question that continues to emerge is that of scalability.

4. Experiments of Non-Linear

The combination of form-finding and digital fabrication can have a major impact on the current design processes. The following two projects utilize non-linear information modeling processes to manifest designs that embark on the conceptual age.

4.1. Mathmorph

The name "Mathmorph" combines the notion of “mathematic” with the notion of “morphology. This project focuses on the study of “mathematic” as an embedded variability of spatial arrangement with procedural model. The influence of digital media and information technology on architectural education and practice is increasingly evident. Digital technology has reconditioned the design process that establishes new processes and techniques of fabrication. This reconditioning has influenced how we operate as architects. Today, architectural design and building construction are increasingly aided by and dependent on digital technology. These technologies allow architects to foresee the appearance and predict the performance of proposed buildings. Mathmorph proposes an interdisciplinary research in digital fabrication of unconventional 3D forms on a conceptual design level in order to explore their features in interacting with people and their potentials of being used as architectural forms. It describes an experimental approach which facilitates 3D form generation, visualization and fabrication. First, a series of computer models were generated using computer algorithms, and mathematic equations[ii]. Secondly, a series of 3D models were generated by importing these computer algorithms and mathematic equations into 3D programs. These computer models were fabricated as physical prototypes by the FDM systems, CNC machine, and laser cut machines. The purpose of this part is bi-fold. It does not only inspire designers to use unconventional 3D forms in architectural design, which has traditionally been restrained by the difficulties in design and visualization, but also tests the possibility of these unconventional 3D forms in being manufactured as physical prototypes.

The use of these mathematically driven forms can generate porous structures that are non-site-specific and allow for maximum heat gain/loss and natural wind-flow. By interlocking two forms the generation of natural program issues solve themselves; for example a mix-use program naturally forms based on the two independent forms. The computational approach to design allows for two areas of interest in the architectural field to combine: digital form finding and digital fabrication.

A series of abstract sculpture designed with the focus on its potential transformative spatial layout was also explored. The generation of an abstract mathematic form using equations was studied. These forms showed the unlimited possibility of interlocking / intertwining between solid form and void space. We adapted several variables to control the repetition and resolution of these interlocking spaces, by an exhaustive combination of several variables values. From a large number of outcomes, only several ideal spatial arrangement solutions were selected by reviewers and then used as the genotype for the next operation.

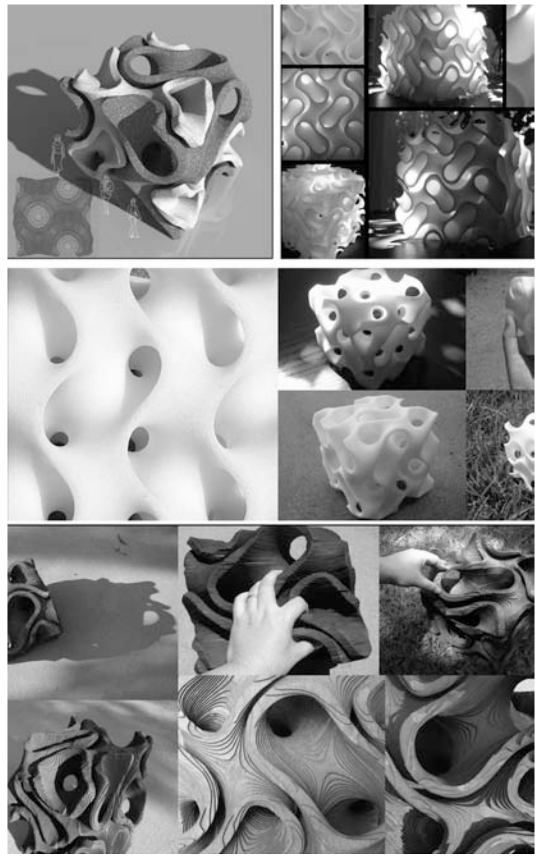

Figure 5: Mathmorph project - digitally fabricated prototypes

After exporting this parametric model into 3D programs, the continuation to building its procedural network was allowed through a non-linear information model. A sequence of deformation and control nodes were added. This additive information evolved independently in order to yield a more fabrication friendly form. As a result, we created a high degree of complexity and explored the dynamic possibilities of spatial arrangement with relatively simple input information. In this process, the information model demonstrated itself with a great power and an unlimited potential of form exploration from sets of parameters. The reviewers selected the desired control nodes and manipulated them to create the new spatial organization. This processes verified thata parametric model can be optimized by the limitations of digital fabrication. In the final step, a slice node was introduced into the network as a static representation for laser cutting (fig 5). The contouring process produced the file documentation that was needed to digitally fabricate the form. The parameters of the laser cutter and 3D printing were well integrated into the information model. Another input variable, *time*, as the 4th dimension, was also added to snapshot all the layout possibilities into a motion. Expressions were evolved and various spatial arrangements were produced as the value of *time* was smoothly animated. Hundreds of the contour lines for laser cutting were captured into a single morphing animation.

4.2. SWELL – Fab.Lab

Swell is an interdisciplinary collaborative effort of student in four different majors; Architecture, Industrial design, Furniture design, and Graphic Design. The objective of the project was to design an installation that encompasses the visitor within the space and allows for people to be submersed within the context and alter an individual's typical journey. Swell poses a fabrication challenge that deals with scalability. The design problem was that the only digital manufacturing tool available is an 18"x32" laser cutter.

The solution of the author in this scenario was to generate a surface parametrically that would be sectioned and fabricated in a half-lap style joint (fig. 6). The designers wrote a grasshopper script that took into account the individual panel that would be laser cut in order to verify their size compared to the laser cutters bed size. A non-linear workflow provided limitations of the surface and also allowed for fabrication to be rapidly assessed in the early design phases.

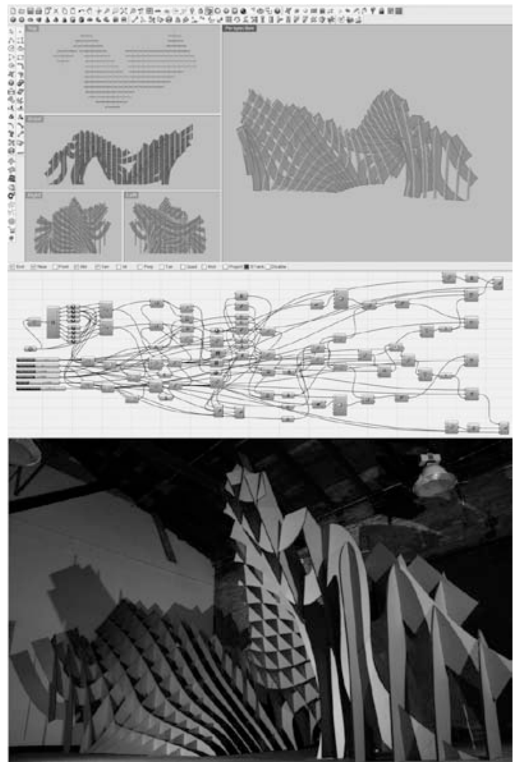

Figure 6: digital design built from Grasshopper script[iii] to built installation

The design of the digital fabrication installation began with two lines that manipulated the gallery space. By parametrically controlling the surface, the design group was able to generate the most feasible and interactive surface possible in terms of fabrication and scale. The surface was developed through a grasshopper script that generated horizontal and vertical ribs - contours. For fabrication processes, the script assessed each rib and broke them down into sections that could be laser cut using an 18"x32" laser bed and cut to precision based on the chosen material thickness. Once the ribs were laser cut, glue was applied to piece them together and ultimately creating the whole rib. Finally, the ribs were slotted together to allow for an installation to manipulate the built environment. The objective of the installation was to maximize the space that it would occupy with the least amount of material and investigate the scale that could be cut using an 18"x32" laser cutter.

5. CONCLUSION

5.1. The benefit of Non-linear Information Modeling

It is proposed that this information model has the potential of being used as a resourceful tool for achieving diversity and complexity in form generation and fabrication. With a minimum input and knowledge of details of all the individual professions, this model becomes one that allows an individual to seek novel and buildable designs. It is the seamless transition between the human brain and the computer processes that allows the architecture field to reach new innovations. These nonlinear information models can be utilized as a platform for future research to build upon. By utilizing interactive information modeling, an individual is realizing the marriage of the dynamic digital and static physical world through an interdisciplinary collaboration that emerges in the architecture field.

The goal of these two projects was to create an engaging experience where architects could control the generation of novel 3D forms in a dynamically changing network. The enormous speed of digital system processed hundreds or even thousands of possibilities in a relatively short period of time. Since forms were generated very quickly, it is advantageous for the designers to choose from a large candid pool instead of carefully adjusting a few models.

In terms of 3D morphology, these processes were considered as psychological change rather than just a form seeking method. “It assists human to observe various possibilities which may not have been thought about before” (Kalay, 2000). With this synthetic approach, we could “consider architecture as a form of artificial life” (Frazer, 1995) and generate creative design solutions. In terms of cooperation, the ability to generate a shared parametrically controlled model often sparks new ideas and directs team members to further exploration simultaneously and collaboratively. Without knowing the details of other parametric nodes outside of the actors focus, designers can easily create a large quantity of forms with a relative short design period and get optimized solutions by concentrating on their “assigned” components.

This process could be considered as a system for helping architects with creative explorations. As fabrication technology matures, it might even be considered as a system which adapts to test various manufacturing system automatically. In either case, it allows the user, computer and fabrication machine to interactively work together in a new way to produce results that no single actor could easily produce alone.

5.2. A New Architectural Language - Fabrication

In order to have architecture re-claim the “master builder” status, designers must learn how to work at a collaborative level and speak the language of digital fabrication. In the past, the traditional language of architecture was expressed though highly annotated section and elevation drawing. Today, the importance of understanding how to model in three dimensions has become an essential portion of an architect’s tools to represent their designs. With a new form of representation emerging in three dimensions, the architect must now learn to speak the language of fabrication that will translate three dimensional models into a machine language – g-code – and allow for a physical realization to manifest. By designing a system that allows for fabrication to be a vital input in the beginning design stage will allow for the architect to speak the computing language. It is then that the architects' documentation is not needed in traditional drawings, but instead translated into the computing language of the machines which allows the designer to again be the one who narrates the construction process without any misinterpretations. (lynn. 2008) Architecture is becoming an interdisciplinary collaboration. The basis of this collaboration will excel when the architect speaks a new language that exploits the idea that the collective whole is more powerful than the singular.

5.3 The Constraint of Non-linear Information Modeling

Compared with the success of BIM within the AEC industry, one constraint of the non-linear information model for digital fabrication comes from the missing of "performance analysis nodes". In our experiments, we can only apply this network to generate various forms and then test their performance afterwards with performance simulation software such as EcoTech or IES. Form fitness evaluation was exclusively applied outside the network. Neither Mathmorph model nor Swell model "seeks" forms based on the performance criteria.

This constrain could be overcome by filling the gap between the slow complex evaluation routines and the large quantity of solutions quickly generated from the network. In an ideal design environment of generating pleasing and complex forms, designers and fabricators will be able to continouslly optimize computer's exhaustive search and modeling power by monitoring the form's structure performance, air dynamic, material cost and other analytical components. Thus, guiding the form seeking process within architectural the known concepts and rules. Once this process is achieved, the information model can be used as a synthetic assistant and driven force.

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[i] Paine's machine made sculptures with various forms driven by the mutation, similar as the identical embryos can be developed into different cells. This genetic-transformation philosophy can be traced back to his earlier projects like New Fungus Crop, and Amanita Field. Although they were created with totally different approach (SCUMAK is Mechanical and New Fungus Crop is botanical), these projects share a similar configuration that is heightened by examine the relation between individual and group, the contrast between the

various outcome and predefined procedure. In Paine's sculpture making machine, auto-mechanical and computer controlled manufacturing technology resembles nature such as Chaos theory, which was executed in the computer programming level to produce unpredictable geometric forms.

[ii] sin(2*x) * cos(y) * sin(z)
+ sin(2*y) * cos(z) * sin(x)
+ sin(2*z) * cos(x) * sin(y) – 0.06 + cos(2*x) * sin(y) * cos(z)
+ cos(2*y) * sin(z) * cos(x)
+ cos(2*z) * sin(x) * cos(y)

[iii] Portions of Grasshopper script taken from Andrew Payne of LIFT Architects