Understanding Parametric Modeling as a Novice-

A First Person Perspective

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Abstract

This exploration uses autobiographical design as a research method to investigate how to foster a foundational understanding of parametric design systems as a novice in design. This study explores the interplay of tangibility as it relates to helping designers in understanding parametric modeling and gaining fabrication awareness. The goal of this research is to use my experiences from the exploration as a way to understand how to help other novices in design, like myself, in understanding complex concepts reflected in digital fabrication.

1. INTRODUCTION & MOTIVATIONS

Computational systems have become fundamental to artists, fabricators, designers, architects, and more. However, while digital fabrication tools make it possible to customize objects, what can be readily made is limited. As design fabrication tools become more advanced, they become increasingly complex. In other words, we have traded handmade craftsmanship for the ability to rapidly design, test, and manufacture. As a result, the learning curve for the adoption of these design tools widens the gap between human interaction and digital fabrication. Computer aided design (CAD) systems aid in the development, refinement, analysis, and/or improvement of a design. CAD also makes it easier to share designs with peers or coworkers who may be local or remote, given the ability to send and edit a digital design, over the internet. These systems vary in their intuitiveness, as it can be challenging to understand their underlying computational principles. Digital fabrication technologies are generally specific to their respective hardware, thus requiring each designer to have sufficient domain knowledge. Therefore, it is often challenging to understand CAD system's underlying computational principles, and how these principles relate to the geometry as well as materials one uses for manufacturing.

Current digital fabrication technologies enable new opportunities for the creation of complex shapes, yet they also serve as intermediary between design and construction. As the set of technologies known as rapid prototyping (RP) emerges and is absorbed into practice, it is being recognized as a technology of great potential significance for design (Sass, 2005). Rapid prototyping uses CAD data in order to quickly fabricate a scale model of a physical object. Conventional methods for RP generally start with using CAD applications to create digital representations of designs for physical objects. What makes CAD fundamental to the modern design and manufacturing process is the software's use of parametric modeling, which allows designers to change the geometry of a model by modifying its dimension's values. In other words, parametric modeling software defines the dimensions of a model, while CAD user interfaces allow designers to interact with and manipulate the design. There has been an increase in emerging research concerning how to engage designers with parametric modeling systems due to their importance in the prototyping and fabrication processes (Zheng, 2017). While rapidly prototyping with CAD systems has made design faster and more efficient, designers often overlook the importance of choosing the proper fabrication machine and materials to build a rapid prototype. It has become easier to make scaled models by leveraging rapid prototyping and CAD, yet there needs to be a greater emphasis on the choice of tool one uses to create a model, respectively. Different fabrication tools, such as a laser cutter or 3D printer, generally, cannot produce the same model due to their varying limitations and abilities. Advances in digital fabrication tools have resulted in a new discipline that is focused on user engagement, design cognition, and computational systems. Human Computer Interaction (HCI) research is increasingly focused on how designers can better engage with digital fabrication techniques throughout the design process. It studies how people interact with computational systems, and to what extent the users are able to interact with digital technology. One of the main goals of HCI is to create successful interactions between both the digital technology and the user. There is an opportunity in finding new ways to aid designers in understanding complex concepts reflected in the fabrication process through interactive learning experiences.

This paper investigates how to foster a foundational understanding of parametric design systems, which function as the underlying framework of design software and various digital fabrication technologies. This research is motivated by the interplay of tangibility as it relates to assisting designers in understanding complex concepts that are reflected in the fabrication process. The opportunity to tinker with materials facilitates users in a discovery of inherent affordances, possibilities, and constraints in relation to fabrication. Additionally, this research is motivated by how I can use my own experiences to help other novices in design in gaining a better understanding of parametric design, and fabrication awareness. This investigation is based on the foundations of autobiographical design: design research drawing on extensive, genuine usage by those creating or building the system. This practice is based on true needs of the researchers, rather than the assumed needs expected of targeted users. The idea is that as the researcher(s) build the system, they use it themselves, learn about the design space, and evaluate and iterate the design based on their own experiences (Sengers, 2012). Autobiographical design advocates the learning-by-doing principle. Learning-by-doing is the act of learning from experiences that result directly from one's own actions, as contrasted with learning from reading existing research, or listening to others' instructions or lectures (Reese, 2011).

1.1 Motivation

As a student at the University of Colorado, I was introduced to digital fabrication and became increasingly involved with fabrication technologies. In particular, I was drawn to the Mcor Iris 360 paper based 3D printer described above. Having no prior knowledge of 3D printing and digital fabrication tools, I was intrigued by the ways in which the machine uses paper as material to create high-quality models. For these reasons and the reasons that I outlined earlier, I was more eager to approach the Mcor than the more commonly used 3D printers such as a Lulzbot. There has been limited research on the machine, given there is only one Mcor printer at the University of Colorado. 3D printing and laser cutting is a widely known skill used in labs at the ATLAS Institute, however few are familiar with the Mcor machine's SDL fabrication technique. Due to its unique qualities, I felt the Mcor was more approachable. Additionally, given its uniqueness, the machine was always available to use, unlike other 3D printers at the university that are more popular. Lastly, since few students had previously used the machine, I was more drawn to the Mcor because other students who are unfamiliar with it could potentially benefit from my experiences and findings while using it. I was therefore inclined to learn to use this machine with the goal of understanding its capabilities as a fabrication technology. I found that learning CAD software and 3D printing was challenging due to my lack of knowledge in software, machinery, mathematics, and modeling. However, my exploration of digital fabrication technologies helped me to understand several of the complex concepts behind digital modeling, and rapid prototyping. As I became more familiar with fabrication and parametric modeling, I found that there was an opportunity to help designers gain a foundational understanding of computational design systems and conceptual concepts seen in digital fabrication technologies.

1.2 Research Outline

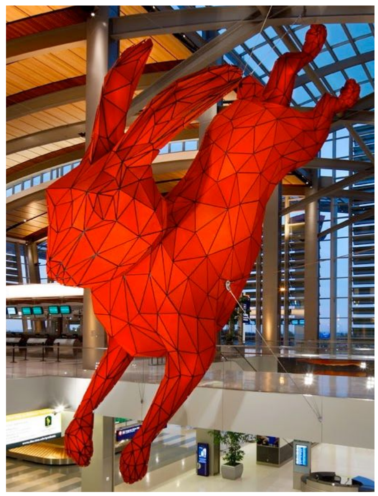
The research conducted can be grouped into three parts. First, I investigated the capabilities of Mcor Iris 360 3D printer and laser cutting as RP technologies. In doing so, I explored the opportunities and challenges faced as a beginner while learning parametric design, and fabrication technologies. Additionally, this led me to further explore how to overcome some of the found challenges. The findings from the exploration were then used to develop a framework for a workshop framework to help users in analyzing and understanding parametric design. The workshop proposed is aimed to facilitate an engaging and interactive learning experience in a collaborative workspace for novices in design, like myself.

2. COMPUTER AIDED DESIGN, PARAMETRIC MODELING, AND DIGITAL FABRICATION

2. 1 How Computer Aided Design is Used for Rapid Prototyping

Rapid Prototyping (RP) is described by Ryder et al. (2002), as a method for fabrication, by which physical descriptions of design ideas are created in the early stages of the design process. RP can be used to integrate designers into the process of building artifacts as part of the creative design process. For instance, architects explore many design possibilities through design sketching, hard-line drawings and physical models, manufacturing artifacts for the exploration of diverse ideas (Kroes, 2002). Various industries utilize RP to depict design concepts in physical models. Art and design are two domains where the synergy of programming and digital fabrication offers unlimited new opportunities for creative expression and exploration.

Digital fabrication modeling is a design and production process that combines 3D modeling or computing-aided design (CAD) with manufacturing technologies. Unlike traditional paper-based methods for design, digital design implies designing exclusively within a computational environment. Architects, designers, and fabricators use these advanced methods and digital technologies to aid them in their development of models in virtual space. Rapid prototyping makes use of these aided digital technologies to rapidly design, edit, and fabricate models. Conventional methods for RP generally begin with learning CAD software in order to rapidly create digital representations of design ideas for physical objects. CAD applications such as Fusion 360 and Rhinoceros, allow users to generate stereolithography (STL) files, which are digital blueprints of 3D designs. CAD softwares can be used to create two-dimensional (2-D) drawings or three-dimensional (3-D) models and aid designers in the creation, modification, analysis, and optimization of a model. Designer Lawrence Argent is one of the various artists who uses CAD to aid in the creation of large scale geometric works of art. The Leap sculpture which is on exhibit in the Sacramento International Airport is one example.



Lawrence Argent's 56-foot-long aluminum sculpture (Kreysler)

The sculpture depicts a 56-foot-long red rabbit, and stands as the centerpiece of the airport's art installations. The work consists of 1,446 aluminum triangles, which were developed using CAD software.

Digital fabrication tools extend traditional forms of fabrication by allowing for new levels of automation, precision, and fabrication speed in producing one-off physical objects (Eisenberg, 2007). CAD software is often used to increase productivity, improve design quality, and to document design processes for manufacturing. The increased utilization of CAD software to generate three-dimensional models has resulted in a new way of prototyping, by using computational systems to create complex models without the need to physically design and create them by hand. While these modern design systems and technologies improve the speed by which designs become prototypes or products, they can result in an abstraction and removal from the object one is creating.

2. 2 Understanding Parametric Design Systems and Algorithmic Logic

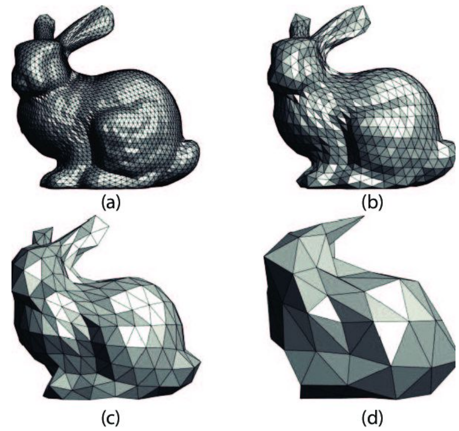
Over the last several decades, computational enhancements in the field of digital fabrication have become increasingly utilized and have made digital prototyping tools prominent in design, prototyping, manufacturing, and fabrication. Especially in architecture and design, parametric modeling scripts are often used with CAD software. Algorithmic logic is of significant importance to parametric design software. Parametric design systems are based on an algorithmic construct, which makes their adaptability and responsiveness, to changing design criteria, extremely efficient throughout the design process. An algorithm is a set of instructions that fulfills a clearly defined purpose in a number of steps. When algorithmic logic is used in conjunction with CADs, redundant work is scaled and automated. Algorithmic constructs require users to define parameters in order to generate a series of geometric operations, which produces the final object. Parametric modeling tools allow designers to rapidly make iterative changes to a model. Parametric modeling tools enable designers to explore an array of design options, render alternatives, and improve designs in real-time (Aish and Woodbury, 2005). On the other hand, making changes to a model without using parametric design is a much more time-intensive process, as it requires users to re-create each of the elements specified in a model, manually. This repetitive and tedious process of manually editing each element of a design, is one of the limitations of CAD that parametrics design systems provide a solution to. Conventional CAD tools are concerned mostly with the representation of the final design form and make it inefficient for users to revisit possible design alternatives in real-time and make rapid edits. Rather, parametric modeling software enables its users to optimize for the design, and efficiently explore variations of the model, in real-time by scaling and automating the algorithmic logic that otherwise would have had to be done to each parameter, manually. When parametric modeling is used in conjunction with CAD, the problem of redundant work is eliminated and the goals of the rapid prototyping process are better achieved.

2. 2. 1 What is Grasshopper?

One of the benefits of using Rhino is the ability to utilize additional plugins, such as Grasshopper. Grasshopper is an algorithmic modeling script for Rhinoceros (Rhino), CAD software that uses a visual programming language developed by architect and computer scientist, David Rutten. It is a parametric design tool that is used for geometric design, fabrication, engineering, and architecture. Grasshopper's algorithmic modeling scripts create 3D geometry (points, curves, surfaces, etc.), which can then be referenced back in Rhinoceros. Creating designs in Grasshopper involves placing visual code elements and connecting them with an input/output known as wires. The resulting forms are modified with parametric sliders. Once the parameter values are set, they are then “baked” into Rhino. This is used to add the previewed geometry to Rhino, so that it can be manually modified, exported, etc. For models that are designed in CAD or with parametric modeling software, rapid prototyping devices provide an efficient workflow, throughout the conceptual design (Sass, 2009).

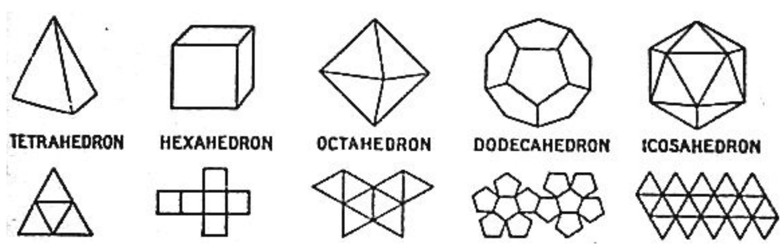
2. 3 Fundamentals of Geometry in Digital Design

Geometric concepts provide artists, architects, and designers with sources of inspiration, representational means and structural verification of forms (Bertol, 2). Computational design tools like Rhino and Grasshopper require the utilization of several mathematical concepts in order to generate digital models. One can manipulate a shape or form and study alternatives by changing the variables, parameters, or defined geometry of an object or assembly (Oxman et al. , 2010). In doing so, they also require users to have a fundamental understanding of these concepts. Having a fundamental background in mathematics and geometry is becoming increasingly important for designers with respect to using digital fabrication technologies for the development of 3D models. CAD softwares allows for designers to rapidly break up any object into polyhedra by using a mesh. In geometry, a polyhedron (plural polyhedra or polyhedrons) is a three dimensional shape with flat polygonal faces, straight edges and sharp corners or vertices. CAD systems like Rhino enable users to create a mesh from any structure. A polygon mesh is a collection of vertices, edges and faces that defines the shape of a 3D object digitally. Rhino has many features that allow users to manipulate form geometry. For instance, the ReduceMesh command in Rhino decreases the polygon mesh face count of an object.



(Decreasing the polygon mesh face count of a bunny)

Geometric nets are another mathematical concept often reflected in CAD softwares. A geometric net is a flattened out three dimensional shape. When the "net" is cut out, folded and assembled together, it creates a representation of a three dimensional shape. The net of a polyhedron must in general also specify which edges are to be joined since there might be ambiguity as to which of several possible polyhedra a net might fold into. Algorithmic scripting enables designers to computationally create new forms, using variations of the platonic solids. There are exactly five platonic solids; Tetrahedron, Cube, Octahedron, Dodecahedron, Icosahedron.



(5 Platonic Solids and their 2D nets- Mathworld)

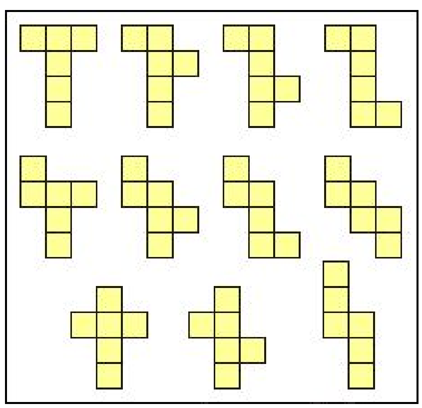
These 5 shapes are the most basic building blocks that structures can be reduced to. In three-dimensional space, a Platonic solid is a regular, convex polyhedron. It is constructed by congruent (identical in shape and size), regular (all angles equal and all sides equal), polygonal faces with the same number of faces meeting at each vertex. The platonic solids are named by the ancient

Greek philosopher Plato, who theorized that the classical elements were constructed from the regular solids. Every physical structure can be reduced and explained using the platonic solids.

Platonic solid	number of nets
cube	11
dodecahedron	43380
icosahedron	43380
octahedron	11
tetrahedron	2

(Buekenhout and Parker (1998) compute the number of nets for the 5 Platonic Solids- Mathworld)

There are many ways a cube's surface can be broken down by geometry. A cube consists of six square faces, twelve edges, and eight vertices. When the faces of a cube are separated at the edges and laid out flat, they make a 2D figure, which is known as a net. There are eleven different variations of nets for a cube.



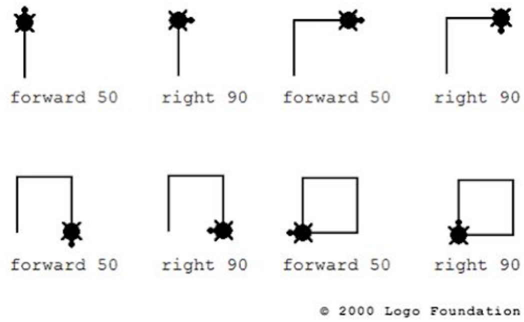
(The 11 nets for a cube- Math Forum)

The Platonic solids can be described as forming the basis of all structure. Current digital fabrication tools allow users to use algorithmic constructs to generate geometric models based on automation and operational goals rather than just aesthetic ones.

2. 4 Importance of Physical Models in the Design Process

Physical modeling is one way through which designers realize mental concepts (Cuff, 1992). Models can help in analyzing and understanding the context of the design by intuitively conveying design concepts and facilitating collaborative work. As a design representational medium, the model making process can lead to new forms beyond the original concept (Sass, 2005). Manipulation of external design representations has become a key component in enhancing design cognition and exploration. Simondetti shows how physical models aid in advancing the cognitive processes of design by using physical representations that demonstrate various properties of the model (Simondetti, 2002). This practice promotes noticing, play, and exploration. When designers are given the opportunity to tinker with materials, they can discover the inherent affordances, possibilities, and constraints in relation to fabrication. Creative fields are characterized by the generation and manufacturing of objects for reflection and evaluation (Schon, 1983). As designers engage with physical models, the focus becomes more an exploration of the design components and less the characteristics of the software and machinery. A characteristic of these approaches is that RP can potentially support a comprehensive and integrated environment to study form, space making and the physics of materials relative to machine processes in construction (Sass 2005).

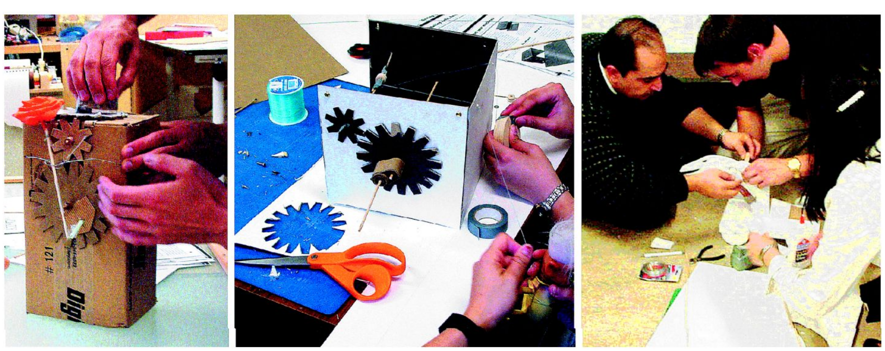
One example of research in this field looked at ways to teach children biomechanics by allowing them to build a physical-mechanical arm, as opposed to drawing or computer modeling an arm (Penner, et al. , 2000). The emphasis of this study was on learning concepts by using physical manipulation and component assembly as a way to understand design in the natural world. This research reflects a term coined by Papert in the 1980s, Constructionism. Constructionism emphasizes knowledge building through activity-based learning during educational development. Papert developed the concept of Constructionism as a technical apparatus for teaching children mathematics by computer programming. Papert argues that constructing virtual artifacts using digital computational tools plays an essential role in creating meaningful relationships between designers and physical artifacts. Papert elaborates on this concept through the use of programming environments such as Logo, in which children construct their own knowledge through physical representations of abstract concepts (Papert, 1980). At the time, the goal was to use Logo as a system for students to relate mathematical and computational concepts. By interacting with their environment, they could better understand the result of the programs they were creating Logo.



(Student engaging with the Logo environment. A display turtle preceded the physical floor turtle.)

While Papert's constructionist lens was focused on children learning mathematics, a similar approach for expert and novice designers is also beneficial.

Camarata, Gross, and Do offered a three-credit physical computing studio in the department of architecture at the University of Washington, Seattle (2003). Their research consisted of facilitating a studio to explore the use of computationally enhanced artifacts and environments in the learning process. In the first phase of the studio the instructor provided students with a background in architectural design and construction and computationally enhanced artifacts. The studio then introduced the fundamentals of electronics and microcontroller programming. It was designed as a traditional architectural design studio, fostering creative thinking and encouraging hands-on learning. The physical computing studio acts as a way to understand various ways for enabling students to explore computationally enhanced artifacts and environments.



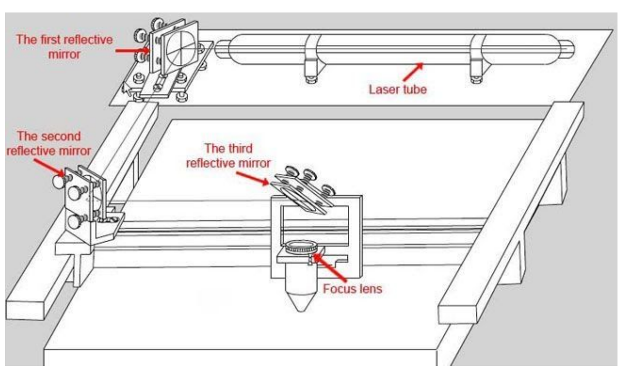
(An exercise for model assembly introduces mechanical movement and material exploration)

2. 5 Types of Fabrication Methods

Rapid Prototyping extends the learning of digital fabrication concepts by engaging the designer with materials and machine processes similar to those used in construction. By finding ways to create meaningful connections between computational design concepts and physical artifacts, it is possible to aid novice designers in overcoming the gap between digital design and human interaction. The conjunction of digital-fabrication technologies with tangible artifacts in design serves as one such connection. While the deployment of new prototyping technologies and methods play an integral role in production of functional prototypes, they also enable new opportunities for designers to use tangible artifacts as visual aids during the design process.

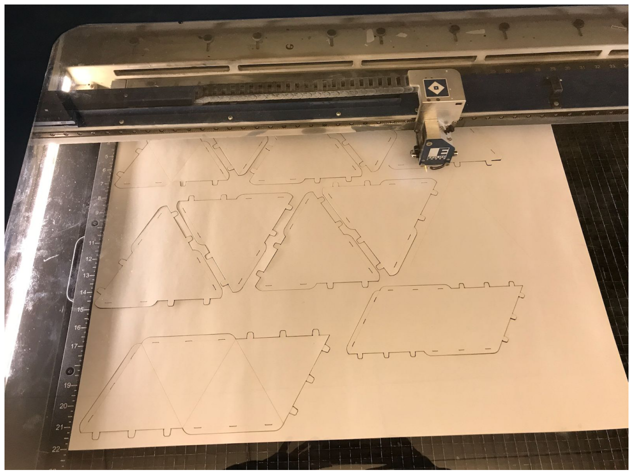
2. 5. 1 Two categories of Fabrication Technologies: Subtractive and Additive

Subtractive fabrication technologies cut forms from a sheet or block of material. An example of a subtractive fabrication technology is laser cutting from a flat sheet of material. Computer Numerical Control (CNC) laser cutting commonly uses optics, an assist gas, and a guidance system to direct and focus the laser beam into the workpiece. Laser cut models require descriptions in the form of 2D shapes from 3D models. The produced flat components are then folded or assembled into a three dimensional structure.



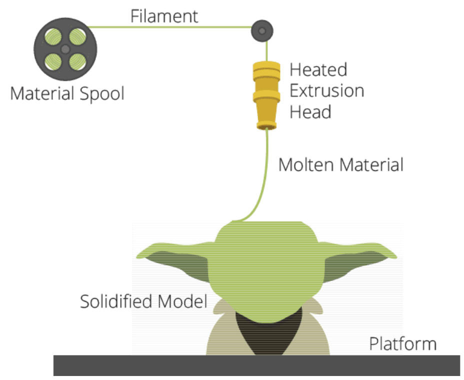
(CNC laser cutting process)

A key benefit of subtractive manufacturing is that it preserves most of the structural properties of the materials being cut. However, subtractive fabrication is generally limited to one material per part. Also, subtractive technologies generally have limited ability to 3D objects. For instance, laser cutters can only cut outlines and engrave on to a material, making it challenging for designers to design and fabricate more complex models using this subtractive process.



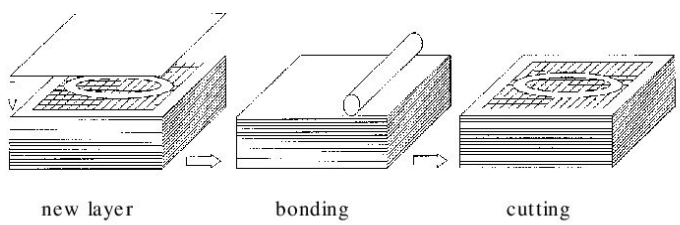
(Laser cutting surfaces of tetrahedra (also known as nets) on cardstock paper)

Additive fabrication techniques, such as 3D printers, create objects by adding layers of material onto a build platform. This enables many degrees of freedom with respect to designing both the overall shape and the internal structure of objects (Mueller, Baudisch, 182). The most common form of 3D printing, Fused Deposition Modelling (FDM), utilizes the extrusion of thermoplastic material. The process works by melting plastic filament that is deposited, via a heated extruder, one layer at a time onto a build platform, according to the 3D data supplied to the printer. Each layer cools and hardens as it is deposited and bonds to the previous layer.



(Process of Fused Deposition Modelling)

Laminated Object Manufacturing (LOM) manufacturing is a lesser known additive manufacturing process where an object is created by successively layering sheets of build material, bonding them through heat and pressure and then cutting them into the desired shape using either a blade or a carbon laser.

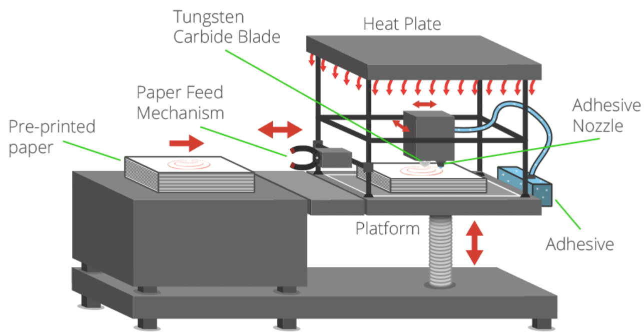


(Layer-Object Manufacturing)

2. 5. 2 Selective Deposition Lamination

As fabrication technologies are becoming increasingly popular, there have been several new additions of these two fabrication categorizations in order to combat some of the limitations current fabrication technologies faced. One example of a developed addition of LOM manufacturing is known as Selective Deposition Lamination (SDL). Selective Deposition Lamination is a paper-based 3D printing process whereby sheets of paper are cut and bonded together to form a 3D object. This process is used by the Mcor Iris 360. The Mcor Iris 360 was introduced in 2007 by Mcor

Technologies (now doing business as Clean Green 3D), a company that manufactures paper-based 3D printers. The Mcor printers use low cost materials — standard copy paper, water-based white glue, and ink, all of which are fully recyclable. Mcor devices use a 2D printer to render the color print on each layer of paper. The machine precisely cuts away non-object material then laminates the layer(s) onto the existing stack.

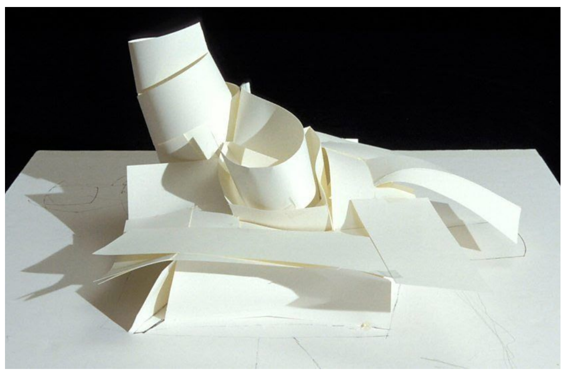


(Selective Deposition Lamination Process)

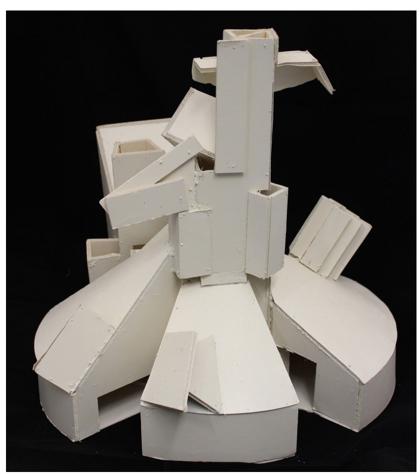
2. 6 Affordances of Paper As an RP Material

Compared to plastic, paper is inexpensive, accessible, environmentally friendly, and can enhance creative expression. Paper is a modest material with rich affordances for craft and design (Zheng, 2019). Paper has many advantages, as a material for rapid prototyping, given its physical characteristics and different compositions. Paper is flexible and can be shaped into different objects using few layers. Several prototyping methods that use paper as a material are usually used solely for representations of models and design ideas, given their fragileness and complexion in assembly. While this material can produce delicate structures, it also offers the opportunity to construct robust structures by using multiple layers. Another benefit of using paper as a material for RP is it is cheap. Due to the low cost of paper, it is accessible and can be widely used for prototyping across many fields and design disciplines throughout the early stages of any design process. There are differing methods of using paper for developing design ideas. One of the most remarkable examples of this is seen through the work of Frank Gehry. His design practice consists of building complex shapes as physical models made conventionally of paper. Frank Gehry constructs hundreds of models during every project.

Peter Sims' book *Little Bets (2011),* describes how the famous architect Frank Gehry comes up with designs for new buildings. Sims writes that Gehry starts the design process by "literally cutting up, crumpling, and folding pieces of paper or corrugated cardboard with colleagues. " Portrayed in the documentary *Sketches of Frank Gehry,* the paper being used is sturdy enough to be folded into rectangular structures. After the paper is assembled into building components, the blocks begin to resemble a rudimentary building. "The initial prototype that emerges over an hour or so barely looks like a building," Sims writes. "But it's merely a starting point. They have begun and can work quickly and inexpensively to explore dozens of initial possibilities. Staring at it, Gehry smiles and says, 'That is so stupid looking, it's great. '"



(Model of Gehry's first UK building (Dundee Maggie's Centre))



(Architectural Model, Sheet Metal Structure, by Frank Gehry, 1987)

Designs are later realized for construction through the use of parametrically based software and CAD manufacturing techniques (Lindsey, 2001).

Kirigami is another traditional method that has been used for the construction of paper models, whereby one cuts, folds, and bends flat sheets of paper into three-dimensional forms. Kirigami enables users to shape paper into pliable structures that move dynamically to afford tangible interactions. Today, kirigami is applied creatively across diverse contexts, from the fine arts to nanoscale engineering; and even as a point of intersection between these different fields (Collins, 2016). Research led by Clement Zheng at the University of Colorado extends the work on paper-based interfaces by exploring the affordances of kirigami for tangible interaction. The research explores a range of haptic feedback delivered by different kirigami objects. Their work reveals that by utilizing various cutting and folding patterns, these objects multiply the material properties of paper to afford coherent interactions such as pushing, stretching and twisting (Zheng, 2019). The insights were then used to develop products that offered different tangible interactions for HCI.

(The interactive kirigami design schematics can be accessed and edited by opening this PDF with an application like Adobe Illustrator, Sensing Kirigami (2019)

3. Limitations of Fabrication Technologies

While rapid prototyping has been applied to a variety of fabrication and design disciplines, these areas often have different specification requirements, which are limited by existing fabrication technology. Some limitations of modern rapid prototyping technologies are: accessibility, complexity of interface, speed of manufacture, design manipulation, and overall quality and accuracy models which result from RP methods of modeling. These limitations can require designers to compromise on certain key aspects of the intended design and prototype model.

3. 1 Lack of Accessibility

While fabrication technologies such as 3D printers and laser cutters become more common, these technologies are not yet widely available to consumers due to their high costs and steep learning curves. Using conventional CAD systems and modeling scripts, to develop rapid prototypes, is generally a complex task for novices to digital design and fabrication. Many potential users may consider computer programing to be too highly specialized, difficult, and inaccessible, leaving one with the impression that this skillset will only have relevance as a career path, rather than as a mode of personal expression (Resnick, 2005). Given the current inaccessibility of fabrication technologies to wider audiences, and challenges associated with learning the required skill sets to use them, potential designers continue to be limited in their ability to design, develop, and fabricate products and prototypes.

3. 2 Expensive High Quality Color Models

One of the challenges that designers face with manufacturing high-fidelity, rapid, prototypes is the high cost. There are a limited number of technologies that are accessible today that can achieve a full-color spectrum. One of the existing technologies that is able to print high quality, full-color models is the Mcor IRis 360, which uses the SDL process. It was invented in 2003, by brothers Dr. Conor and Fintan MacCormack, as a way to address the soaring prices of 3D printers, and their materials. The MacCormacks' vision was to make high-end prototypes more affordable and accessible, by creating a 3D printing process with a low operating cost (SDL). This vision resulted in the inception of Mcor Technologies and the invention of the Mcor Iris 360.

3. 3 Challenges in Domain Knowledge

While digital fabrication technologies enable designers with many new opportunities for RP, they also present challenges to the design process. These tools often require designers to immerse themselves in digital representations and concepts that they may not be familiar with and are often an abstraction from the physical object one is trying to create. For instance, parametric design tools require domain knowledge in computation and mathematics, fields that not all users have been fully educated in. In other words, using these technologies may result in a more efficient design process, yet they require an investment in time and in abstraction upon the design process.

3. 4 Materials and Build Speed

One of the challenges faced with current 3D printing technologies today is the limitation of materials. Currently, plastic is the most commonly available material for 3D printing due to its ability to adapt to different 3D printing processes. Polylactic acid (PLA) plastic is widely used for prototypes of solid objects and components. Plastics used in 3D printing such as PLA have several limitations as a rapid prototyping material: they can be expensive and designers are generally limited by their material properties. 3D printed models using these plastics are generally hard to touch, making it challenging for designers to incorporate softer and more tactile material characteristics in their design. Additionally, due to the nature of the fabrication process, 3D printing tends to be slow. It often takes hours to print a small 3D model, and so designers are often limited by both the size of what they can construct and the time it takes to print. Another challenge of commonly used 3D printing materials is that they for the most part cannot be recycled. As they are becoming increasingly popular within the fabrication industry, this is a challenge that needs to be addressed.

3. 5 Model Assembly

Joinery design is also interdependent on several other factors of the fabrication process, particularly concerning the material properties of the model and the conceptualization of assembly methods. Digital fabrication tools also enable designers with new opportunities for developing assembly components using computationally generated joints. The primary function of joints is to hold different components of the model together and aid in the transformation of 2D parts into a functional 3D structure. Joints impact the efficiency of model assembly. For instance, models that have a method of tabs or joints for assembly are much more challenging to put together by users, as joints that require adhesives often slow down assembly time compared to joints which provide an inherent connection. Joint design can often be a tedious and complex task, as it requires the consideration of several fabrication factors. Tightening the fit between the dozen different parts of an assembly, or changing the type of joint, can be daunting not only for novices but professionals as well, especially when each detail has to be reworked (Mueller, Baudisch, 2015). Given that several existing CAD tools, such as laser cutting, do not take different fabrication methods into consideration, designers are often required to independently integrate fabrication awareness into the digital process before manufacturing.

3. 5. 1 Joinery Software

Clement Zheng led an investigation at Georgia Tech on use of laser cutters as a model-making tool embedded in the industrial design process. While laser cutting is powerful and commonly used as a subtractive fabrication process, designing laser cut assemblies is a complex task, especially for novices. Zheng developed Joinery, a toolkit that generates parametric joints for laser cut assemblies. It mitigates the tedious task of recreating assembly parts for joinery during the iterative process of creating laser cut assemblies. Users define edge-pairs as connections. Once a joint has been defined, the system provides users with immediate visual feedback by highlighting the joint connections between the pairs of edges. The system enables the designer to use a customizable set of parameters for each joint profile. The software generates joints that are responsive to design and fabrication edits defined by the user; joints are dynamically updated due to their parametric nature. These parameters allow the designer to configure the joint profile to suit the materials and design specifications. To support collaboration, the software enables users to export joint profiles. Zheng and his colleagues (2019) concluded that Joinery simplified designing joints for laser cut assemblies, expanding students' ability to explore complex forms, and offering them the flexibility to efficiently use different materials.

4. EXPERIMENTS IN DIGITAL FABRICATION WITH PAPER

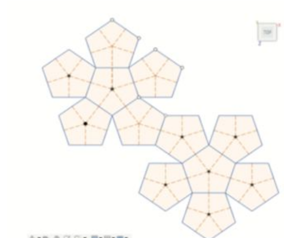
4. 2 Methods of Discovery

This research uses a constructive approach by developing parametrically generated construction kits. The construction kits contain different components that are used to assemble physical models. The hands-on nature of these kits can aid designers to conceptualize and evaluate complex concepts through physical and visual criteria. The design goal is to develop 2D nets of shapes that can be folded and assembled to create a larger 3D structure. The hypothesis is that these tangible artifacts can aid designers in understanding digital fabrication concepts and can facilitate material exploration.

I explored two different fabrication processes to create models using paper. The exploration began with understanding how to use the Fusion 360 CAD software to construct flat nets of the platonic solids, and then to fabricate them using the Mcor 360. The second process consisted of using the Rhino modeler and the Grasshopper parametric package to develop models for laser cutting.

4. 2. 1 Phase 1

Phase 1 began with using Fusion 360 CAD software to model faces of the platonic solids flattened, creating the 2D nets of the shapes. This first step was conceptual as it served to identify how each 3D shape could be broken down into a flat surface so that I could construct it in Fusion 360.



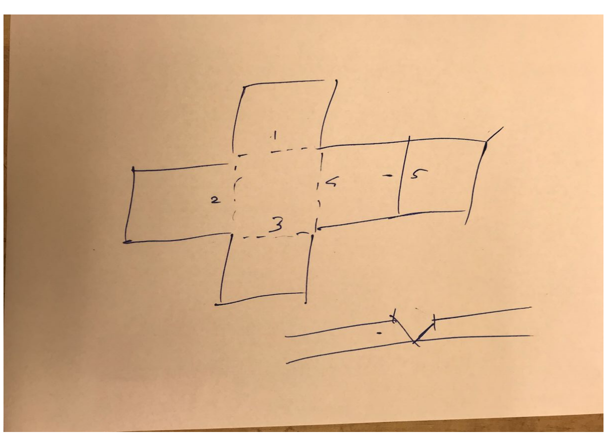
(Part 1 of Modeling Regular Dodecahedron Net)

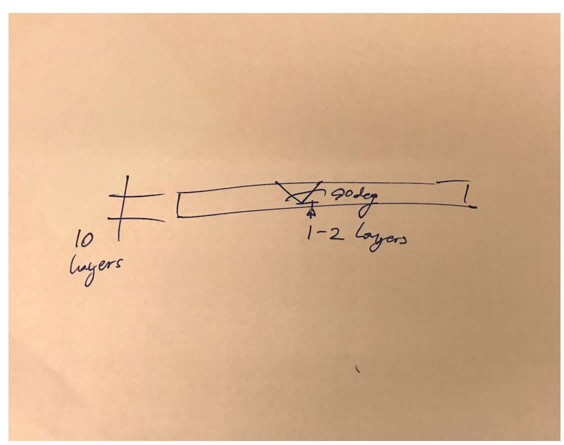
One of the advantages of using SDL is the opportunity to enhance 2D models by adding dimensionality so that the models can be more structurally sturdy when assembled. Surfaces constructed using a single sheet of paper are very delicate, so these models are not structurally sturdy and will not withstand forces. On the other hand, surfaces constructed using twenty sheets of paper result in a more robust form that can withstand more force than a single sheet.

Given the opportunity offered to enhance 2D models using additive fabrication is that the designer can add/ extract volume and create texture on these nets using CAD, which is often challenging when using a subtractive process like laser cutting. Once the 2d nets were constructed, I extruded each face to add dimensionality. While considering the thickness of the digital models in relation to the Mcor 360, I was able to conceptualize this better given my knowledge of the SDL process. Through my exploration of paper as a material for RP, I began to take different factors, such as thickness, into consideration when creating these models for the Mcor. Each layer in the 3D print is the thickness of a single sheet of printer paper, . 1mm. When modeling these nets in the CAD software, I was able to apply my material understanding to the design because I had fabrication awareness and an understanding of the material properties.

To design geometric nets of platonic solids that have dimensionality to them, I had to consider the use of beveled edges on the different faces so that the user could easily fold the net together. A beveled, or chamfered, edge of a structure is one that is not perpendicular to the faces of the piece. A beveled edge generally refers to the angle that one surface makes with another when they are not at right angles. In the net of a cube, the edges of each face must have 45 degree angles, so that when folded, they face together to form a 90 degree angle.

In order to create these beveled edges, I used the chamfer tool to cut the edges at the required 45 degree angle. In addition to the beveled edges, I found that a supplementary gap is needed between the faces to account for the tension created when folding the net into the intended structure. Therefore, I left . 3mm remaining for the base so that the faces still could be attached and folded into a cube.

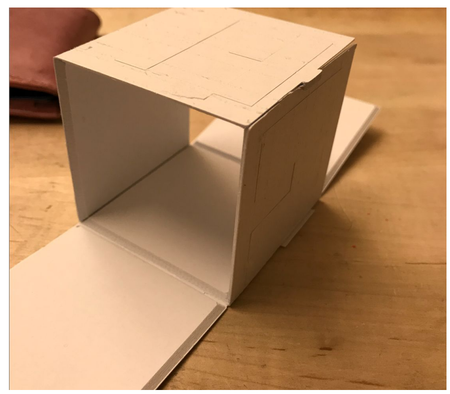




(Sketches of the beveled edge in relation to the net and supplementary gap needed to hold the faces together to aid in conceptualization of design)

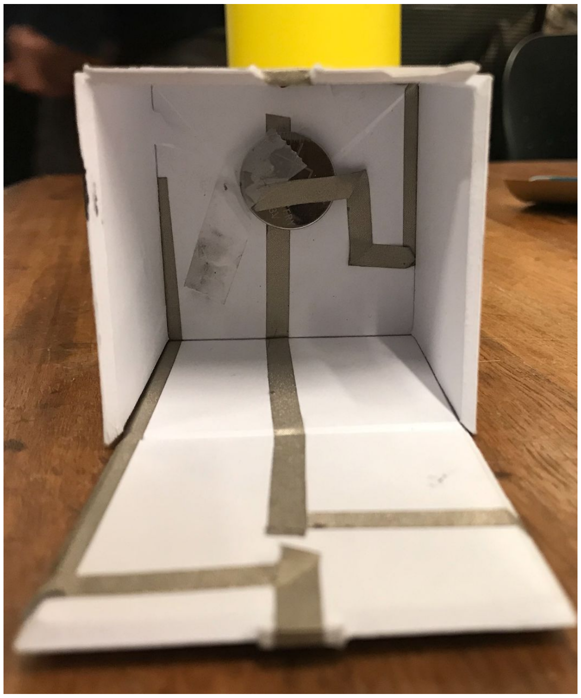
To enable efficient structure assembly of the nets, I also had to consider methods used for joinery so that the user could assemble the structure more easily and without adhesives. My first attempt to create joints was by manually designing them in Fusion 360. I added trapezoids to act as tabs on the edges of the surfaces so that the net of the cube could be folded together and assembled without the need of glue or tape. This required several iterations, as I had to test different types of tabs to understand how to design them to be functional.

(Sketching on model to aid conceptualization of joints)

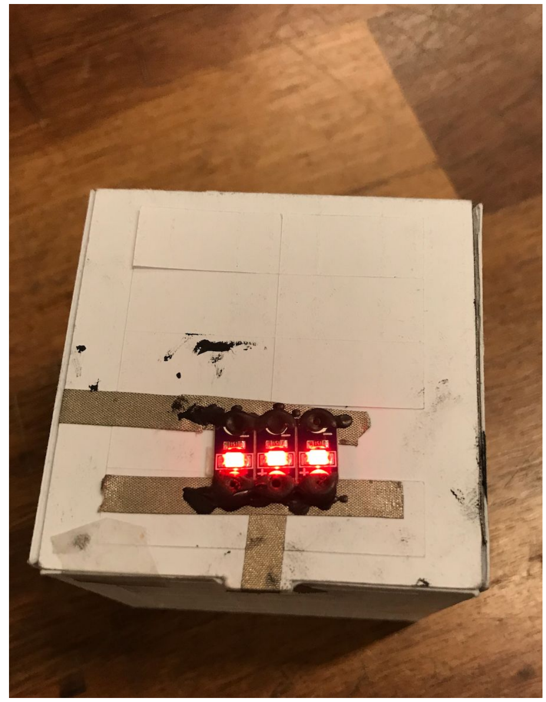


(Evaluating designed joint)

I was interested in finding out whether including electronics to the shapes could make exploration more engaging, since it would add another level of interaction, in addition to folding. I began exploring different conductive materials and ways to include simple electronics. I found that a simple design for the electronics would be beneficial so as to not detract from the concepts being learned, but to simply enhance users' experience. I used a coin battery, copper tape, conductive paint, and LEDs. The copper tape was connected to the battery and put on the inside of the cube. When the faces of the net are folded together forming a cube, the circuit is complete and turns on the LEDs. This exploration resulted in the open ended question of if the use of simple electronics can enhance these models and make the learning process more engaging.



(Copper tape, and coin battery circuit)



(LEDs turn on when the cube is folded together)

My experiences from phase 1 provided me with direct knowledge on how the difficulties that a novice in digital fabrication may face while becoming acquainted with the underlying mathematical concepts used in fabrication. Additionally, by manually constructing nets of the platonic solids, I was able to gain a better understanding of how this process could be simplified by using parametric modeling.

4. 2. 2 Challenges Phase 1

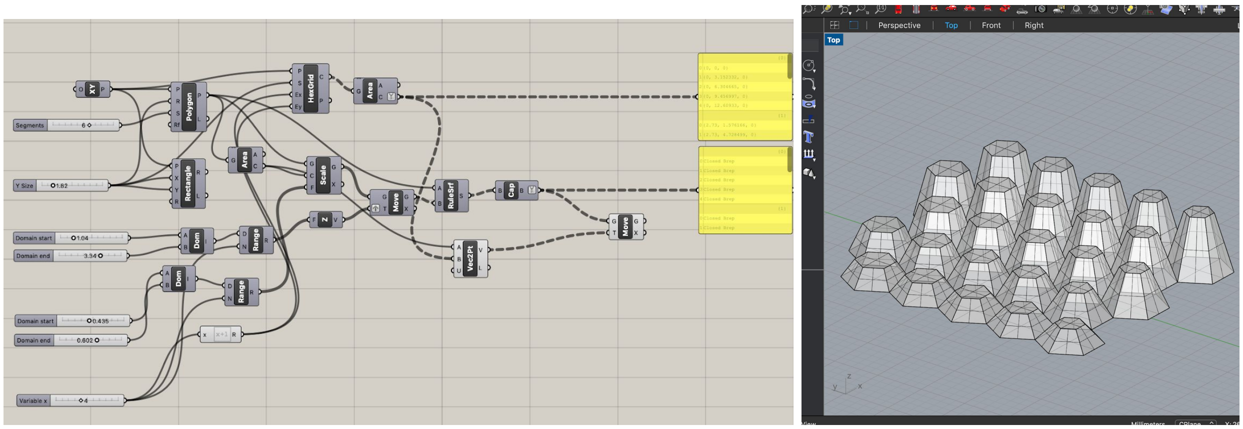
Most of the challenges I faced were about domain knowledge in the software. I was constrained in the expression of my design ideas because of the complexity of CAD software, and the fundamental understanding one needs in mathematics, materials, and computational systems in order to successfully employ it. For instance, I found there were several conceptual mathematical concepts I needed to become acquainted in order to create a successful model. One challenge I faced was the conceptualization of 3D shapes into 2D nets. Using Fusion 360 to manually design the nets required understanding of how 3D shapes can be turned into 2D nets, and vice versa. Another challenge was that it became more difficult to realize the angle at which the edges needed to be cut, specifically when modeling the nets of more complex shapes such as a dodecahedron. To overcome learning these conceptual concepts, I found that it was very helpful to get assistance from other designers. Investigating these complex topics in a collaborative environment aided me in understanding different ways to conceptualize and visualize these concepts.

In addition to the challenges of using CAD to express design ideas due to the required domain knowledge, I discovered that the process overall was extremely time intensive. Since I was constructing these nets manually and had no prior experience using fabrication technologies, I was very limited by time constraints. Not only did it take a significant amount of time for me to become acclimated with these using technologies, the design process itself also was very limited due to the fact that required so much manual work, thereby making it difficult to rapidly prototype these models. For instance, while designing the thickness of nets and proper joints for assembly, I needed to get direct feedback from the physical models in real-time. This process was a very iterative cycle as I had to keep on modifying and re-evaluating the changes made to the model. Given that the digital modeling process was manual, it was very difficult to rapidly make changes to the model so that it could be efficiently printed for evaluation.

4. 2. 3 Phase 2

The second phase of my design exploration was to use Rhino and Grasshopper to parametrically create the models for laser cutting. Given the unavailability of the Mcor Iris machine, I was interested in how laser cutting can be used as an alternative method to create paper models that can be folded and manipulated to aid in understanding complex concepts. Given that the laser cutter is a subtractive fabrication process, it has limitations when compared to the Mcor. However, the laser cutter also has its own benefits, being that it is much more accessible than the Mcor, and is faster for manufacturing.

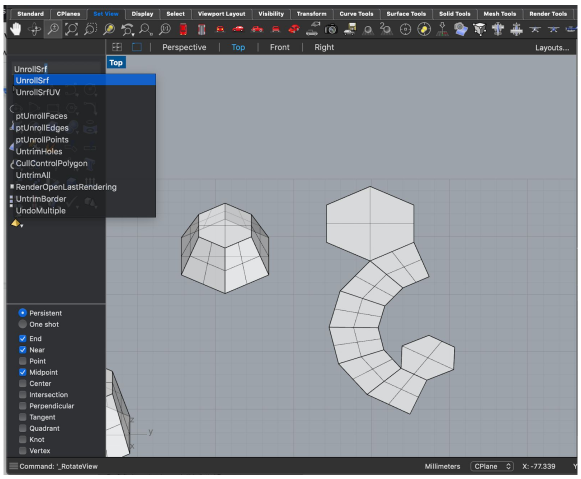
To become familiarized with the Grasshopper plugin, I watched several different tutorials and was guided by an instructor of the Form class in the ATLAS Institute. I essentially created a 3D hexagonal shape in Grasshopper and modified it to create a larger parametric design. Using grasshopper enabled me to rapidly create the shape and modify its attributes so that I could find the best set of parameters for the structure. This was done by creating definitions outlining the design process in Grasshopper, so that a structure can be computationally created using the defined parameters.



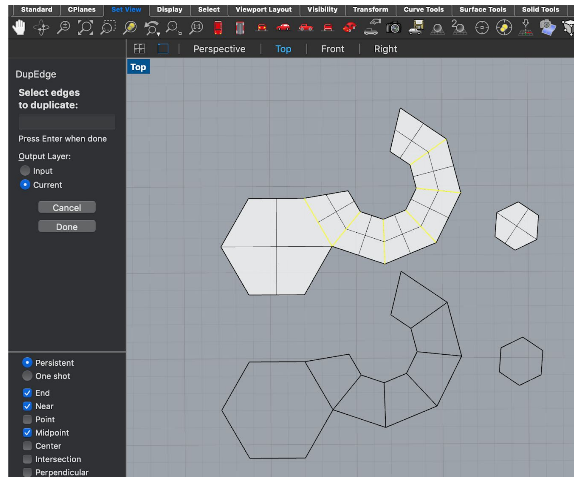
(Grasshopper definitions (left) used to create the parametric model in Rhino (right))

The process began by using a segment slider to define how many sides the shape should have. I found that a six-sided shape is more interesting to fold together than a three-sided shape because it is more intricate and therefore more engaging to manipulate. I then created a definition to modify the 2D hexagon to transform into a 3D shape. The y-size slider dynamically changes the size of the base hexagon. The first pair of domain start and end sliders are used to define a range for the height of each side on the shape. The second pair of domain start and end sliders are used to define a range to scale the size of the surface hexagon on the top of the shape. Lastly, the variable x slider defined how many times the shape should be the instance, I used a segment slider to define how many sides the shape should be created. Increasing variable x adds more shapes to the structure, allowing the structure to reflect a more gradual shape change based on the defined range.

After setting all of the parameters in Grasshopper, I baked it into Rhino so that I could then continue to modify the structure. Another benefit of using Rhino to develop geometric nets is the unroll function. The unroll function simply flattens out the surface of a 3D model. This flattened surface can be considered to be a net. Due to my limited domain knowledge in Grasshopper, I decided to manually unroll each shape using the unroll function. Grasshopper can be used to make this manual process faster, but in doing so it also becomes a more complex process to generate in the script. Unrolling the shapes makes it make possible to laser cut the structure as several different components.



(*Unroll command to flatten surface)*

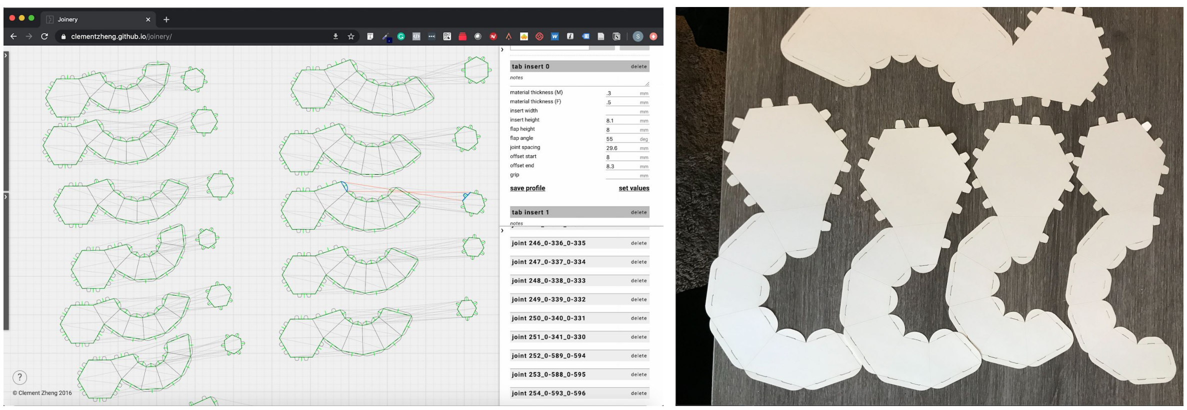


(Copying border and edges of net for laser cutting)

Once the shapes were unrolled, I exploded the net which basically ungroups the faces. This step was required so that I could remove the top piece of each shape, so that tabs for assembly can be added without overlapping and also for the purpose of using vellum for the top of each 3D shape, and cardstock for the body. Once the top of the shape was separated, I rejoined the net so that I could easily duplicate the borders and edges for the purpose of adding tabs to each nets in Joinery before laser cutting it. Since laser cutters only recognize outlines and borders to cut/ engrave, the process of duplicating the borders and edges ensures that the outlines of the model are recognized so there are no issues while processing the laser cut file.

4. 2. 4 Joinery Software

For these components to be assembled into the desired structure, I used Clement Zheng's Joinery software to test and add tabs for assembly. After experiencing several challenges of designing and modifying joints using CAD, I was compelled to use this software. By using tabs for model assembly, the focus becomes more on the experiences, values, and concepts learned through manipulating these folded paper models, instead of the actual assembly (glue, tape, etc). One of the main benefits of using this software was the ability to rapidly change the parameters of 350 joints to laser cut different materials and to explore different types of joints without needing to spend much time on modeling them individually. The joint profiles saved on the software interface were helpful as I did not need to spend time in the design of the joints individually and thus, could focus on the different combinations of values for the parameters to create the most efficient assembly process. The developed RP system utilizes the tab insert joint profile that was developed for paper-based materials and foldable plastic sheets. This tab was very beneficial because it supported my goal to require no external fasteners or adhesives. Tabs can be inserted ‘blindly’ (i. e. from one side), making it possible to fold together 3D geometries from flat nets.



(Tabs added to the unrolled surfaces of the parametric model using Joinery and the laser cut result)

While experimenting with different types of assembly methods, I found that Joinery enabled me to easily take material properties into consideration during the design process. Given that my exploration focuses on how paper can be used for the construction of these models, using the laser cutter enabled me to explore different types of paper, which is something that the Mcor does not support. I found that cardstock was a valuable type of paper for constructing models. Cardstock, also called cover stock or pasteboard, is a paper stock that is thicker and more durable than normal writing or printing paper, but thinner and more flexible than other forms of paperboard. Another type of paper I came across during my material investigation is vellum. Vellum is a unique type of paper that is strong and also translucent. I found that the incorporation of vellum in the models could help facilitate the user’s material exploration. This material exploration could help facilitate material awareness through the manipulation of physical components in the construction kits. The incorporation of vellum in the models offers several opportunities to make these kits more engaging. By building off of my findings from phase 1, I found that vellum can also be used as a way to essentially create a translucent "lid" on the shapes, allowing for light reflected from an LED to be projected from inside the shape. These LEDs are mounted onto a coin battery, and held together by a binder clip. The LEDs are sand papers down so that the light diffuses better. These construction kits act as guides to aid users in making meaningful connections between material properties, digital fabrication concepts, mathematics, and creativity.

(Assembly of Parametric Model)

4. 2. 5 Challenges Phase 2

As previously mentioned, laser cutting is limited in comparison to using the Mcor for fabrication. For instance, it can only manufacture models by cutting their outline, and engraving while the Mcor has more opportunities in adding additional volume and texture to surface nets of models. It is also very difficult to add beveled edges using laser cutting. I tested this theory by attempting to engrave a 45 degree angle onto wood. It was noted that this was not an advised use of the laser cutter, due to the dangerous nature of using a laser to create these precise angles. This disadvantage leads to limitations in materials that can be used to fabricate geometric nets. Cardstock is thin enough so that there are no issues when folding the nets, yet it also produces delicate models. On the other hand, using a material like wood to manufacture the nets using laser cutting would be more difficult. This process would be more challenging because the design requires additional manufacturing at each edge of the surface, given the way the edges would overlap due to the material thickness.

Another challenge of phase 2 was the limitations of materials due to their thickness. While cardstock can be used to create models with a desired form, it is still not very structurally stable and cannot withhold large amounts of force. This makes the prototype more delicate, and limited in its ability to represent structural factors. While the Mcor has the ability to automatically layer sheets of paper together and create beveled edges, this process would require lots of manual work for a laser cutter, making it time consuming and inefficient for fabricating.

Grasshopper is very complex, thus it is difficult to use it as a beginner in CAD. Limitations in domain knowledge were major challenges that I faced during both phases. In phase 2, I became acquainted with using Grasshopper to computationally create a parametric structure. This process was time consuming and difficult because it required me to not only understand many different conceptualizations of fabrication techniques, but also to learn a new way of representing my design ideas through an algorithmic construct. While Grasshopper enabled several new opportunities for parametric modeling, I was limited in what I could use it for because of its complexity.

Reflection

My research explored the various opportunities and challenges that novices in design, such as myself, experience when learning digital fabrication techniques throughout the design process. This exploration focused on delving deeper into the underlying concepts behind parametric design and digital fabrication. The principle of learning-by-doing gave me a better understanding of how users engage with these fabrication technologies, as well as the current opportunities and limitations that these technologies present to the design process. For instance, I found that a fundamental understanding of mathematics and geometry is required to efficiently learn and use digital fabrication technologies. During phase 1, of this investigation, I spent more time than I had anticipated on modeling elevated nets of shapes because I had to learn about the various factors that must be considered in order to create these models. The use of beveled angles and joinery were considerations that I had not taken into account, until after I began the modeling process. Discovering the various types of assembly methods, only mid-design, made the process more time consuming. Although less efficient, this process taught me, a novice designer, that I first needed to learn about different joinery methods, prior to developing the models in the CAD software. Confronting the mathematics behind each angle for each face of the net, only late in the design process, resulted in my need to pause designing. At this juncture, I needed to understand the mathematics and geometry behind the desired form in order to continue designing. Having an improved understanding of assembly methods, algebra, and angular geometry would have been beneficial, prior to beginning this design in CAD, as more focus would have been spent on the quality of the design rather than understanding the rudimentary math and geometrical concepts required to fabricate the model.

As my research process reflected the principles of learning-by-doing, I gained a unique perspective that enabled me to approach parametric modeling and digital fabrication as other beginners would. Confronting these topics through my discovery led me to understand why having this fundamental background as a novice in parametric modeling and digital fabrication is useful. This circuitous experience resulted in recognition that for novice designers to efficiently utilize digital fabrication tools and techniques throughout their design process, they must first have a fundamental background in the underlying concepts of CAD softwares and fabrication awareness.

My experiences led me to understand how each design process is dependent on each method of fabrication. This investigation found that the choice of digital fabrication tools is a reflection on the method of fabrication that the designer will use. For instance, I found that the design process differs when fabricating with the laser cutter or Mcor Iris 360 3D printer. Phase 1 consisted of becoming familiar with Fusion 360 as a CAD software to fabricate geometric nets using the Mcor Iris 360 3D printer. During phase 1, using Fusion 360 enabled me to add greater detail to my design of elevated nets because I had more ability to use beveled edges and varying material thicknesses. Since phase 1 ended early due to a peice of the machine breaking, phase 2 primarily consisted of designing models that could be laser cut. I was drawn to use a laser cutter as an alternative fabrication method to the Mcor because of the ability to continue using paper as a material for the models, and also because it is more popular and accessible than the Mcor. Since phase 1 brought me to realize that working with unique machines can be very time consuming due to the difficult nature of getting replacement pieces and/or machine maintenance, I was particularly interested using a laser cutter during phase 2 so that I would not be as held up by troubleshooting as I was by the Mcor. I was unable to use the same models that I had developed in Fusion 360 for phase 2, because laser cutters do not have the same abilities as an Mcor Iris 360 for manufacturing. For instance, a laser cutter cannot create the same beveled edges as the Mcor and therefore limits the users' ability to test varying material thicknesses, since it is a subtractive process. As a result, I used Rhino and Grasshopper as alternative design processes for phase 2. Given that the laser cutter is most useful for manufacturing models that are mostly flat and have straight edges, the process of design is dependent on this method of fabrication. While phase 1 was very time consuming due to the manual nature of the approach, overall it was very helpful because it provided me with valuable lessons and insights into the fabrication process. Manually modeling 2D shapes into 3D objects not only helped me conceptualize how 3D objects would appear flat, but also helped me identify what was repetitive and to understand how repetitive tasks could be automated during phase 2. For example, I found that the task of adding joints to all sides of the model, manually, was very time consuming during phase 1. As a result of this experience, I familiarized myself with parametric modeling in order to further automate my process while modeling during phase 2. When applying this automation to the second phase, I found that CAD software that uses parametric modeling was very helpful when prototyping a product, to be manufactured, with a laser cutter. The use of parametric modeling presents one with the opportunity to enhance the creative process, by further enabling designers with the freedom to explore the geometry of a form. Since parametric design can help designers in automating tedious tasks, it also enables designers to spend more time exploring different form variations since there is more time to focus on the design, rather than the production of it. Since parametric modeling tools such as Grasshopper enable users to rapidly modify the parameters of a design, it is much easier for designers to explore different sizes and shapes. Parametric modeling is also generally helpful when a designer is looking for precision while creating more complex forms.

My research found that while parametric modeling can be effective for modeling repetitive and complex designs, there are several instances where it can also be ineffective. Particularly in early stages of the design process, I found that parametric modeling is not very useful. Parametric modeling requires designers to have a solid understanding in computational systems. For beginners in CAD, I found that it can be a very time consuming and frustrating process to solely rely on parametric modeling tools, such as Grasshopper, while trying to develop a design idea. While these computational systems have become more user friendly over the last few years, they still can be very complex. Given the required domain knowledge to efficiently use these parametric modeling tools, it can be very challenging to use them at the start of the design process. In early stages of the design process, there often is little need for parametric modeling, as it is much easier to use simple sketches for instance while developing the design idea. Sketching can enable designers with more creative freedom during early stages of the design process than parametric modeling, as the designer is not limited in what they can create by knowledge of CAD softwares. I found that the main drawback in using parametric modeling is the limitation in expressing creativity due the complexity of these digital fabrication systems.

Future work

In our post-pandemic future, I hope to evaluate the effectiveness of this thesis's proposed workshop. I received approval from the Institutional Review Board (IRB) to conduct research with human subjects. This workshop will further investigate how participants may or may not benefit from undergoing my exploratory process, detailed throughout this thesis. Additionally, I aim to continue exploring opportunities offered by the Mcor, since I was able to acquire a replacement piece. Given that my Mcor Iris 360 exploration was cut short, I still have various questions I would like to continue investigating. For instance, future research will aim to test the different kinds of textures and varying types of models that can be created using the SDL process. Given the range of opportunities offered by the Mcor, I will also continue to investigate the fabrication technique's affordances, such as its ability to create full color models, which was not previously possible due to the limitations of the software that I was running during the time of this investigation. This future work will also investigate the opportunities the Mcor offers for creating more complex nets, which can be folded together into structurally stable physical models. The goal of this thesis and its continuation is to find improved ways to familiarize and excite students to design and fabricate with the Mcor, given that it currently has limited traction among my peers at the University of Colorado.

Conclusion

This research's mission has been to use my own experiences in order to aid other novices in design in gaining a better understanding of parametric design, and to increase their awareness about fabrication techniques. This thesis reflects the principle of learning-by-doing through an autobiographical design lense. My investigation is motivated by the interplay of tangibility and abstraction as it relates to assisting designers in their understanding of parametric modeling, and gaining fabrication awareness. In order to bridge the gap between digital design and physical fabrications, physical contact is imperative, especially when trying to teach and using parametric design. The mathematical and geometric knowledge, necessary to make these designs, is not elementary and has a steep learning curve. My research examines the process by which tangible artifacts can be developed to facilitate one's understanding of these concepts. By exploring the advantages and disadvantages of parametric modeling and various fabrication technologies, I have opened a window into the means by which learning can be enhanced via the aforementioned technologies.

Appendix

Unfortunately, due to the uncontrollable circumstances, this investigation was unable to achieve its final product– a widely accessible and consistent experience for real life novice designers to improve their understanding of and choice of fabrication techniques and tools. Since fabrication technologies are not yet readily available to consumers, it is challenging to devise a virtual method to facilitate the same experiences students have in a workshop. The current inability to learn through physical interaction currently prevents potential beneficiaries of this research to realize the full experience of the proposed workshop.

The main challenge faced in phase 2 was that my research was limited as a result of the unprecedented time of COVID-19. This pandemic has affected the ways that people interact, conduct their work, and has forced an immediate shift into this new digital era. Given the state of quarantine that people are currently living in across the world and the health risks posed to individuals across the globe, in person workshops are on hold. As a result, designers and researchers are confronted with challenges as to how they can investigate how developed tangible paper models can aid designers in the conceptualization and exploration of parametric design, as well as fabrication awareness. This limitation is a result of the accessibility of fabrication technologies due to the closure of CU campus. Additionally, quarantine has limited the ability to engage students in a hands-on and collaborative learning experience, which was my initial goal. While video conferencing tools have made it possible to rapidly shift education to a completely virtual environment, these tools are still not sufficient for conducting workshops that use physical materials and collaborative learning in design.

Lastly, one of the biggest challenges I faced during my exploration was the availability of Mcor replacement parts and mechanical support. Given its uniqueness, there are very few machines available in the US itself. One of the issues I found while using the Mcor was that the most essential piece of our machine was broken. In specific, the washer that holds the blade that cuts each sheet of paper was missing a piece. This washer is essential because it holds the blade in the exact place for the machine to create very precise models. Having a broken washer therefore changed the precision of the cuts, resulting in a skewed model or print error. There unfortunately are no existing resource guides for the Mcor Iris that cover the specifics of components inside the blade holder because the company itself had gone under and there was no way to contact their support team. Due to the limited information available on Mcor replacement parts, I had to find out how to get a replacement part or fix the existing. This process was very difficult and resulted in the loss of time for designing, since I had to focus on troubleshooting the Mcor. Given my limited prior knowledge in fabrication technology, this process was difficult to tackle due to the limitations of resources available for troubleshooting the machine. During my hunt to get a replacement piece, I was able to get in contact with 3 people in the US that currently have an Mcor Machine, and the former CEO of Mcor Technologies, Dr Conor MacCormack. This was a valuable experience as I was able to learn about the different reasons the Mcor is used as well as the experiences of those who have years of experience with the machine. This also resulted in new relationships with fabricators who have this unique technology extensive experience using it. These new relationships enabled a flow of information with regards to the Mcor. One of the common challenges all people with an Mcor faced was that they had run out machine parts (glue solution, blades), or needed replacement parts. For instance, one person I spoke with in California ran out of replacement blades for the machine, which resulted in inaccurate and dull cuts. Since there was a difficulty in getting Mcor parts because the company was in non-existence, he found someone who specialized steel to make him these custom blades. Another person I spoke with in Colorado had mentioned that they ran out of the glue solution the machine used since he was using the machine so much due to the high volume of orders people were requesting. While he has been trying to make an alternative glue solution for the past year, he has not had any luck. After discussing my broken washer problem, he was able to 3D print custom washers that aimed to be the proper dimensions of the original washer. While these washers seemed to work much better than the ones I had been trying to use, they still were not exact in dimensions, therefore still lacking in cut precision. While briefly speaking with Dr Conor MacCormack, he informed me, "As you may know already I have set up another company and am no longer involved with Mcor. Mcor is in receivership at the moment - however there might be some opportunity for tech support in the future. " About two months after this correspondence, I was contacted by a person I spoke to from Colorado who had an Mcor, and was informed that a new company in Germany, Clean Green 3D had taken over Mcor Technologies and was producing replacement parts for the Mcor Iris. I was able to arrange a call with a member of their team, and found that they had reopened the warehouse where there were several Mcor Iris 360 replacement parts in storage. After a 3 month process of trying to find a replacement piece for the machine, I was able to finally acquire a new blade holder so that the machine can keep running in the future. While the process of troubleshooting was extremely time consuming, it resulted not only in successfully getting the machine to work again, but also in the creation of valuable connections within the Mcor community.

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