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The Maker Movement and Three-Dimensional Printing (3DP) have the ability to engage individuals/consumers in the design and fabrication of interior products, potentially transforming a passive consumer to an active creator. Together, they could have significant impact on the design process, fabrication and distribution of interior products. This thesis aims to research the impact 3DP has on the design process and fabrication of interior products through three methodological phases.

The first phase focuses on gaining a first-hand experience and critical understanding of the capabilities and limitations of 3DP in the product design process, as I engage in a project investigating 3DP as an iterative design tool. In the second phase, I collaborate with a fellow graduate student to investigate the role of 3DP in both the design process and as a final fabrication method for a furniture prototype. Finally in the third phase, I facilitate a 3DP product design workshop, in which undergraduate students are asked to incorporate and examine the role of 3DP in the design process of an innovative new product.

The research and analysis generated through the phases reveal that when used effectively 3DP could significantly impact the design process and the fabrication of interior products. 3DP enables the conceptualization and realization of new forms in product design, as well as, allows designers to evaluate and redesign a product based on the fit, form, and function derived from a rapidly fabricated 3D printed product. However, the results from the third phase illustrate the importance of having familiarity

and experience in 3DP and 3D modeling in order to be successful in fully utilizing 3DP in the design process and as a final fabrication method in product design.

PRINTABLE PRODUCTS: INVESTIGATING THREE-DIMENSIONAL PRINTING IN THE DESIGN PROCESS OF INTERIOR PRODUCTS

by

Christine Zinta Lumans

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Approved by

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Committee Chair

DEDICATION

To all who seek to progress in design through 3D printing technology and to the individuals shaping our world through the Maker Movement,

and

To my amazing fiancé Matt Bozigar, my inspiring family, and my dedicated friends who have helped me through this journey.

APPROVAL PAGE

This thesis written by Christine Zinta Lumans has been approved by the following committee of the Faculty of The Graduate School at the University of North Carolina at Greensboro.

Committee Chair________________________________

Committee Members________________________________

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Date of Acceptance by Committee

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Date of Final Oral Examination

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CHAPTER I

INTRODUCTION

The technological advances occurring in the early 21st century have the potential to transform the process, design, and fabrication of interior products. Conventionally, designers have been the ones creating new products, solving manufacturing problems, and/or fulfilling design-related needs. However, current technology is now not only enabling designers but also individual consumers to generate new and innovative products based on expanded software capabilities and new fabrication methods. This technological shift has the ability to create a real-world impact through its democratizing effects. Filling the void in understanding the most effective utilization of these tools and investigating their impact on the design and manufacture of interior products are significant contributions to the future of design. This thesis examines a crucial paradigm shift that is occurring in the field of product design as a result of the Maker Movement and Three-Dimensional Printing (hereafter noted as 3DP). The Maker Movement can be broadly viewed as individuals entering into an unprecedented world of manufacturing in which they design and make products using digital fabrication (Anderson, 2012). 3DP is an additive manufacturing method that transforms a digital model into a physical object. By facilitating this transformation process, 3DP becomes one of the principal tools underlying the Maker Movement. 3DP has even been designated as the Third Industrial Revolution of manufacturing, changing how we design, fabricate, transport, and store products (Barnatt, 2013). This movement and its corresponding fabrication methods are fostering a new generation of manufacturing and related problem solving, through which individuals—and not solely large producers—are capable of designing, fabricating, and distributing their own products. However, many experts consider this technology's main obstacle to be the lack of awareness of when its application is appropriate (Miners, 2013).

This thesis aims to investigate the role of 3DP in the product design process by exploring 3DP through three methodological phases: in Phase I, I use 3DP in the design process; in Phase 2, I collaborate with another designer in the adaptation of 3DP in both the design process and as a final fabrication method; and Phase 3, in which I facilitate the use of 3DP in the design process by undergraduate design students in a 3DP Product Design Workshop. Thus I utilize experimental, rational, intuitive, and analytical methods, as determined and defined by the Institute for Applied Creativity in the College of Architecture at Texas A & M University. Together they help investigate the impact of 3DP in the product design process.

Research Objectives

As noted above, 3DP is an advancing technology that allows users to design, fabricate, and market their products. Through the Internet, this technology is becoming more available to individuals—as well as commercial producers. This digital desktop tool uses an additive manufacturing process that enables designers to make physical objects in shapes and forms in ways that have never before been possible, thereby opening doors to a world of new and varied possibilities (Kurman & Lipson, 2012). This thesis examines 3DP in the context of interior product design, the design process, product fabrication, and in design education.

Although individuals involved in the Maker Movement are utilizing a variety of digital fabrication tools beyond 3DP, this thesis focuses on investigating the impact of 3DP on the design process and fabrication of interior products. Among the many questions this thesis seeks to answer several stand out: Does 3DP affect the design process and fabrication of interior products, and how? When, and why should designers utilize 3DP in their design work? What are the best ways in which 3DP can be incorporated into the design process? This thesis will also address issues, such as utilizing a third-party 3DP company, in respect to the application of 3DP as a design tool.

Integrating 3DP into the design methodological framework may allow for better concept communication, a more realized understanding of form and function, and a way to realize opportunities in design with greater efficiency than through traditional methods. Through the three designated methodological phases, I explore how integrating 3DP into the creative design process will affect the overall product design. The Phase III research study workshop involves three groups of interior architecture students with varying levels of exposure to the 3DP manufacturing process. The aim of this phase was to gain a better understanding of how the introduction of 3DP affects the students' design process and their product's design. This study was administered in a structured educational environment, which stresses assessing, analyzing and modeling conceptual ideas as vital steps in the design process.

A secondary outcome of this thesis is the development and presentation of a set of guidelines (see Appendix B) for students, designers, and individuals on how to integrate 3DP into their design methodological framework. The guidelines are based on my research and the knowledge and experience gained through activating Phase I and Phase II of the study.

Significance

The significance of this research is to examine and determine the impact that 3DP could have on the design process and the fabrication of interior products. This study also reveals the importance of incorporating the concept of "making" in the design process using 3DP. 3DP has created novel ways to not only design and produce products, but also has the potential to generate greater opportunities for practicing individuals to distribute their products. I expect this thesis to contribute to the body of knowledge regarding 3DP and the Maker Movement as it goes through the devised methodological phases. Although the pilot research study workshop in Phase III aims to incorporate 3DP into the design process of undergraduate students within an interior architecture program, I anticipate the results of the study to extend beyond the classroom environment. It is hoped that the benefits reach general makers and public consumers, since 3DP could enable a more passive consumer to become an active creator. The future impact of the Maker Movement is hard to predict, but this emerging movement that started as a cultural shift is transitioning into an economic shift with the power to democratize manufacturing. Enabling individuals to learn how to get involved and become makers could allow them to drive positive societal change (Hatch, 2013). Encouraging students in a design program to use 3DP is a great place to start.

An important aspect to this research is to understand that 3DP, although having now been around for over 30 years is still experiencing its own technological evolution. From primarily being used for prototyping, it has evolved today as a final fabrication method. Although one might cautiously predict that the capacity for "making" someday will be available in every household with personal 3D printers, debate over the comprehensive impact 3DP could have on the fields of manufacturing, education, architecture, healthcare, etc., continues. However, the technology is here and it is only becoming more advanced. It is also becoming less expensive and more accessible with the progress in software and computing, the utilization of improved materials, and the ever more sophisticated use of the Internet. The final judgment, however, follows the axiom that technology is only as good as the people using it. Therefore providing designers and individuals with a studied body of knowledge of the current applications, benefits, drawbacks, and potential uses of 3DP will enable them to make informed decisions on how and when to utilize it in their design process and as a final fabrication method (Kurman & Lipson, 2012). Education is the key to the success in the effective use of any tool or technology, and 3DP is no exception.

CHAPTER II

REVIEW OF LITERATURE

Technology and digital fabrication are creating new ways to design and manufacture products as well as opening the doors for individuals entering the Maker Movement. The following review of literature identifies and examines the topics encompassing and relevant to this paradigm shift in the design process, fabrication, and distribution of interior products. The topics feature the phenomenon behind the transition known as the Maker Movement; the digital fabrication technique with 3DP modifying the way items are produced; the effect these changes are having on current interior product design, all the way from the initial design process to final fabrication; and what the movement means for designers, businesses, commercial manufacturers, and even consumers.

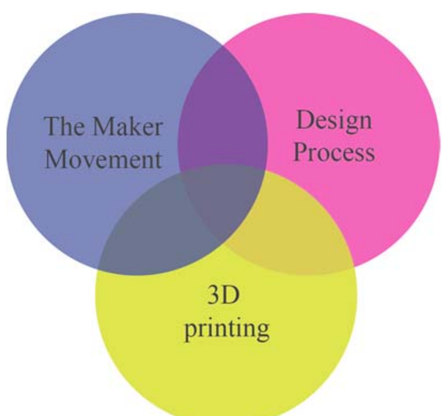


Figure 1. Review of Literature Graphic

The Maker Movement

The Maker Movement began as a cultural shift with an interest in new digital technologies and how these could have a real-world impact as they connected to the Internet. Events such as the launch of *Make* magazine in 2005 and the first Maker Faire gathering in Silicon Valley in 2006 marked the beginning of the movement. The Maker Movement is defined most broadly as people (including but not limited to industrial artisans, designers, DIY enthusiasts, small startup businesses) using digital desktop tools to create designs, and then output them to desktop fabrication machines (Anderson, 2012). "The Maker Movement is the realization by a lot of people that the physical world is a hackable platform" (Frauenfelder, 2012). The movement has gained momentum as individuals have advanced from being passive consumers to active makers of products. Three main characteristics define these "makers": they are digital do-it-yourselfers, who utilize digital tools to craft new products; they consider it part of the cultural norm to share and collaborate these designs with others through online communities. They are also fabricators, fabricating their designs on either their own personal fabrication device or sending their designs to commercial fabrication services or relying on local tech shops offering digital fabricators for individual use (Anderson 2012).

According to Mark Hatch, the CEO of TechShop, "Making is fundamental to what it means to be human. We must make, create, and express ourselves to feel whole. There is something unique about making physical things. These things are like little pieces of us and seem to embody portions of our souls" (Hatch, 2013, pg. 11). These contemporary makers are now transitioning into the mainstream as the consequence of numerous contributing factors, such as technological advances, reduced costs in electronic manufacturing, the current economic recession which has forced many people to repair and/or repurpose items, and finally the resurgence of the community itself (Cole, 2012). With the increase in the number of makers with a growing desire to shape and personalize the goods they consume entering the field and with greater public access to digital fabrication tools, design and production are being revolutionized alongside the democratization of manufacturing. The digital world has enabled this shift in our manufacturing culture, as a growing number of individuals now have access to production tools and the knowledge needed to manufacture objects (Mota, 2011).

The power of democratization is putting the tools in the hands of the people that are willing to use them. One of the critical communication and technological changes of the 21st century is the consumer's desire to acquire amateur content rather than professional via the Internet, which is demonstrated through the rise of Facebook, Tumblr, Pinterest, and Etsy. This transition supports the rise of the Maker Movement and has evoked a liberating response from the manufacturing industry.

> The world's factories are opening up, offering Web-based manufacturing as an on-demand service to anyone with a digital design and a credit card. They allow a whole new class of creators to go into production, turning their prototype into a product without having to build their own factories or even have companies themselves. Manufacturing has now become just another 'cloud service' that you can access from Web browsers, using a tiny amount of vast industrial infrastructure as and when you need it. (Anderson 2012, p. 66)

This manufacturing transformation is creating new possibilities for designers to produce products that were once only possible through industrial mass production. This enables global supply chains to serve the small and the large through both the garage inventor and the big corporation (Anderson 2012).

The twentieth century model of distribution was based on companies developing products profitable enough to produce, popular for retailers to carry, and accessible for the consumer to find via local stores. The Web's influence radically altered this model. Niche products are now transforming the market, as they are driven by the consumer's needs and demands rather than just the companies' interests. According to Anderson (2012), a maker's focus often is on serving the community rather than just making money. The reward of their efforts is demonstrated by the community's response. "Goods made by passionate consumers-turned-entrepreneurs tend to radiate a quality that displays craftsmanship rather than mass-manufactured efficiency" (Anderson 2012, p. 68).

The Maker Movement is not only considered community-based, but it is also driven by yet another democratizing factor, the sharing of knowledge. Online communities exist that allow for designs and information to be shared. One also encounters hackerspaces or makerspaces, which are local venues that allow makers to come together in a shared space to use and/or be trained on how to use various tools and equipment. Participants bring together their individual disciplines, their passion for learning, and unique ideas and expertise that create an environment conducive to inventing and utilizing new technologies and tools. These open-source environments allow contributors to collaborate and improve on each other's ideas or designs, for computer-aided design (CAD) digital files are far easier to modify than having to create something entirely new (Cole, 2012). Makerspaces initially emerged in cities and communities as a place for non-academics to learn and be creative; however, colleges and universities have quickly recognized the value of having such collaborative learning makerspaces on campus where multidisciplinary projects are encouraged ("7 Things You Should Know About Makerspaces," 2013).

> As makerspaces have become more common on campuses and have found their place in public libraries and community centers, their influence has spread to other disciplines and may one day be embraced across the curriculum. Eventually makerspaces may become linked from campus to campus, encouraging joint project collaboration… Makerspaces allow student to take control of their own learning as they take ownership of projects they have not just designed but defined. ("7 Things You Should Know About Makerspaces," 2013)

At the core of the Maker Movement is the reliance on digital design and fabrication tools. These fabrication tools create material objects from digital designs. Laser cutters, computer-numeric controlled (CNC) mills, and 3D printers are the most applied tools utilized in this movement. Laser cutters are mostly 2D devices generating product parts by cutting complex patterns and designs on flat stock with a powerful laser. CNC mills use subtractive technology to cut into sheets of wood, acrylic, metals, and other flat stock to create both 2D and 3D designs. 3D printers employ an additive manufacturing process that builds up objects by depositing and hardening continuous layers of materials such as thermoplastics, powdered resin, glass, and metals. Currently these fabricators can primarily only work in one material at a time. However, the technology is advancing, and as a result increasingly complex fabricators are playing an ever more important role in the rise of the Maker Movement (Mota, 2011).

The Maker Movement and the use of digital fabrication are radically transforming the manufacturing and distribution of products as well as the participating individuals. “Industrial production would merge with personal expression, which would merge with digital design, to bring common sense and sensibility to the creation and application of advanced technologies” (Gershenfeld, 2007, p. 55). Individuals at present have the ability to design and make products either through the use of household personal fabricators, online fabrication services, or local production shops. Products can be customized and no longer have to be sold in high quantities to reach and serve the world market. A new Industrial Revolution is occurring through this movement (Anderson 2012).

> The modern Maker Movement is built on high-tech digital fabrication, and can let regular people harness big factories at will to make what they want. It’s the perfect combination of inventing locally and producing globally, serving niche markets defined by taste, not by geography…These new producers [are] not going to be making the same one-size-fits-all products that defined the mass-production era. Instead, they’re going to be starting with one-size-fits-one and building from there, finding out how many other consumers share their interests, passion, and unique needs. (Anderson 2012, p. 69-70)

By contextualizing the significance of the Maker Movement and its potential impact on the design, production, and distribution of goods, I aim to illustrate the conceptual framework for this thesis. The study focuses its research methodology on evaluating the impact of 3DP in the design process of interior products, which will be integrated within the broader context of the Maker Movement. Gaining a better understanding of the potential impact of this movement and 3DP on society justifies the research effort expended in investigating the effects of 3DP on the product design process. And by conducting a research workshop for interior architecture students on using 3DP in the design process, I am promoting and encouraging the inclusion of "making" through digital fabrication as an integral part of their design education. The introductory knowledge gained could encourage design students to get involved in the Maker Movement, and as they become more familiar and even develop expertise, their future design work could make a positive impact on society.

3D Printing

The birth of three-dimensional printing (3DP) dates back to around 1984 when Charles Hull invented the stereolithography apparatus (SLA), which is a printing process that allowed for a 3D product to be created from digital data ("A Brief History of 3D Printing," 2012). Throughout the 1990s, these 3DP machines were used primarily for Rapid Prototyping (RP) for product development. Early printed prototypes were only being used to help define a product's shape and form and were not intended to last a lengthy amount of time, for the models were quite weak and would deteriorate within weeks of printing. As the technology developed in the past two decades, so has the range of capabilities of the 3D printer. The variety of materials that can be printed has increased, and the process has become faster and more economical (Reeves, 2012). "3D printing technology has been driven rapidly forward by advances in computing power, new design software, new materials, and the rocket fuel of innovation, the Internet"

(Lipson & Kurman, 2012, p.11). From interior home products to orthopedic implants, dental crowns, and prosthetic limbs to the bioprinting of cells, blood vessels, and organs, the number of disciplines that have applied the use of 3D printing is growing (Reeves, 2012).

Principles of 3D Printing

Numerous advantages exist for utilizing 3DP as a fabrication method. As 3DP adapts its capabilities to the needs of the creative digital design world, it bridges the gap between the virtual and the physical, allowing individuals to utilize a design tool as a means of greater control over the physical world. 3DP's additive manufacturing process allows for the production of new shapes of objects and products that have never before been possible. According to Lipson and Kurman (2012), there are ten principles of 3DP that delineate the advantages of this technology. First, manufacturing complexity is cost free, a departure from the traditional manufacturing method, in which the more complex the object, the higher the price. The second principle states that variety is also free. A single 3D printer can produce a variety of different shapes with each print, while traditional machinery is much less versatile. The third principle is that little to no assembly of the final product is required, illustrating the capabilities of 3D printers to produce objects that can form interlocking parts—not requiring the assembly lines of mass manufacturing. Point four eliminates lead time, as 3D printers will be able to print on demand when a product is desired, which precludes companies storing high quantities of stock. Principle five entails liberating design capabilities, enabling 3D printers to utilize the capacity of the creative digital design world to fabricate far more complex shapes.

The sixth principle points out that 3DP does not require manufacturers to fabricate objects themselves, since the design file provides information to a subcontracted printer, a feature leading to new business models. The seventh principle acknowledges the compact and portable nature of a 3D printer. Compared to traditional manufacturing methods, which can only produce objects smaller than the machine itself, 3D printers have the capabilities to create products larger than the printing bed itself by offering a higher production capacity per square foot. The eighth notes 3DP's additive manufacturing process, which only uses the amount of material required to fabricate an object. This method leaves less waste by-product, which is especially significant when manufacturing with expensive and hazardous materials like metal. This idea is also an example of how 3DP could be a more sustainable fabrication process. The ninth principle relates the ability of 3D printers to create an infinite number of material shades. As multi-material printing technology increases, so will the ability of a printer to blend raw materials that can create an unexplored palette of materials with unknown visual and structural properties. And the final 3DP principle alludes to its ability to replicate physical objects. As the technology of scanning improves, one may cautiously predict that 3D printers will be able to utilize a 3D scanner to scan, edit, and duplicate physical objects as exact replicas, or even to improve on the original. Some of these principles are already being implemented as technological advantages of 3DP. Others are still in their early stages and will be applied more as technology advances (Lipson & Kurman, 2012).

One of the most attractive aspects of 3DP is its ability to fabricate complex geometries that cannot be produced using other method such as traditional plastic injection molding (Reeves, 2012). 3DP facilitates customization and individualization of products, enabling the manufacturer to produce no identical items, if so desired. This fabrication process has the ability to produce personalized products according to a person's exact need or want (Anderson, 2012). "Designers are exploiting this geometric flexibility by enabling greater levels of product differentiation. In the end, no 3D printed product ever needs to be the same." (Reeves, 2012) This concept is one of the more persuasive drivers of the shift occurring in manufacturing as a result of 3DP. This thesis intends to test, and then analyze select advantages of 3DP through each phase of the research methodology in order to gain a better understanding of the impact of 3DP on product design.

Small-Batch Production and Customization

The transition from mass-production to small-batch production is an undeniable impact of 3DP and the Maker Movement. The factories and assembly lines of mass-manufacturing allow for an inexpensive way to produce identical items in high volumes; however, there are still numerous costs involved in order to make these companies successful, such as the thousands of molds used to make plastic products, the engineers and technicians behind scenes, and the idea of economy of scale. Economy of scale is what lowers the cost of these assembly line products for the consumers and what increases profitability for the company. Companies have to sell huge amounts of identical items in order to turn a profit from its initial investment. In order to benefit from the economy of scale, companies must resist the urge to change the design of a product unless there is a large demand from the population, for which then they would be willing to risk the investment. The loss in variety of products is a definite sacrifice that occurs with mass-produced products. 3DP, however, offers a new path that combines the benefits of mass-production with the customization and versatility of artisanal craftsman (Lipson and Kurman, 2012).

A disadvantage of 3DP is that it does not allow for economy of scale, as there is no cost savings between printing the first product and printing the thousandth product. There is no volume discount, since each price is calculated on a per unit basis. However, this weakness of 3DP paradoxically also offers its premier advantage: it is able to change and customize each individual product, or it can produce a product in small quantities (Anderson, 2012). 3DP is optimal for small-batch production, which allows for increased product variance, expanded design freedom, potential product personalization, a new retail experience allowing the customer to engage in the product's design, the ability to address an aging and changing population, and an environmentally conscious supply chain as companies reduce stock and waste from production (Reeves, 2012). 3DP also lowers the risk and cost of introducing new products into the market, enabling entrepreneurs to try out numerous ideas with less financial risk. "By starting small using 3D printed production, a new venture does not have to invest in the machinery and infrastructure associated with today's manufacturing environments" (Kurman & Lipson, 2012, pg. 57). In effect, 3DP and the Maker Movement offer small companies and individuals opportunities to enter the same market and have access to many of the same design and production tools as global corporations, but with less financial risk.

3D Printing and Sustainability

Another factor when considering 3DP as a manufacturing method is its sustainability and its effect on the environment. For numerous reasons current thinking suggests that 3DP will become a more sustainable manufacturing method. Few or no transportation costs are involved because products can be printed locally. There is little or no waste because the additive process uses little to no more raw material in making the product than is needed. And finally, since products using this method can be customized, individuals may be more likely to value and keep a custom-made personalized object for a longer period of time (Anderson, 2012). Another advantage of customizable 3DP is not having to store unsold products, as is usually the case of a mass produced object. With 3DP companies print only what is needed, which is not only a financial benefit on sales, but retailers do not lose money dumping products that did not sell. Also other products can have extended lifetimes because owners can print complex replacement parts, which enable them to fix a broken product rather than throw the entire item away. Recycling is also easier because 3DP products are primarily made from a single raw material (however, this is changing as technology increases), and there is no need to disassemble and separate materials (Rydberg, 2012). A significant drawback and cause for concern is that with 3DP's ability to rapid-prototype, "our environment may be littered with quickly discarded print-on-demand plastic novelties” (Lipson & Kurman, 2012, p.11). However, there is hope that

> Personal fabricators will be able to disassemble something and sort its constituents, because the assembled objects are constructed from a fixed set of parts. The inverse of digital fabrication is digital recycling. An object built with digital materials can contain enough information to describe its construction, and hence its deconstruction, so that an assembler can run in reverse to take it apart and reuse its raw materials. (Gershenfeld, 2007, p. 13)

A source of encouragement is a recent study at the MIT Media Lab concluding that “mass customization over the entire product lifecycle is indeed more energy-resource efficient than is mass production” (Lokitz, 2013). It is important to note that 3DP has not yet become mainstream, so it is hard to predict what the exact effect will be on the environment, but there is reason to believe “green” consequences will result from 3DP and the Maker Movement (Lokitz, 2013).

Limitations of 3DP

As with most new technologies and tools, there is not unbounded optimism with 3DP. Currently some material limitations exist that require technological improvements to overcome. 3D printers can primarily print only one material at a time, and not all materials can be printed. 3D printing demands a high cost because manufacturing machines and the materials are relatively expensive and comparatively slower than conventional mass production. Another main limitation with 3D printing is insufficient knowledge of the process and all its consequences. Many individuals and companies do not understand either how to work with it or lack appreciation of the benefits or value it could contribute within their supply chain (Reeves, 2012). “[The companies] current manufacturing supply chain feel vulnerable, their product designers don’t fully understand how to exploit the geometric benefits, and their marketing functions struggle to understand how to integrate 3D printing into the customer value chain” (Reeves, 2012). As technology advances, these issues and limitations will diminish, permitting 3DP to enter not only the world market, but also potentially individual, private homes.

Understanding the opportunities that 3DP can offer, from the favorable customer experience to the commercial and environmental value of the technology, is a critical prerequisite for its success as a business investment. “For some companies 3D printing is a silent enabler—making the companies’ lives easier. For others, 3D printing is the ‘hook,’ the reason the product exists, the differentiator. Once companies understand how 3D printing can add value, then they need to understand how to use it and when to use it” (Reeves, 2012).

Product Design

In order to understand more fully the advantages and to realize the benefits of the Maker Movement and the 3DP fabrication method for the successful design of interior products and accessories it is necessary to review different aspects of product design, from the initial design process to the final manufacturing method. “In creating a product, a designer has many factors to consider: the choice of material, the manufacturing method, the way the product is marketed, cost and practicality, and how easy the product is to use, to understand” (Norman, 2004, p. 5). Exploring the fundamental aspects of product design as well as how 3D printing and the Maker Movement can be integrated into the design process, examining the fabrication of products, and evaluating design pedagogy is crucial.

Product Design Process

An important aspect to the theoretical framework of this thesis is understanding the product design process and design thinking, which will enable a better understanding of how 3DP could be impactful. The product design process can be described as a sequence of phases, in which designers go through steps to identify, ideate, solve, and implement a solution to a problem (Brown, 2008). The design process can comprise of stages of analysis and synthesis in order to develop a final conceptualized design solution (Poldma, 2009). Design thinking is the design-specific cognitive activities that designers utilized throughout the process, and according to Brown (2008) is "a discipline that uses the designer's sensibility and methods to match people's needs with what is technologically feasible and what a viable business strategy can convert into customer value and market opportunity" (Brown, 2008, p. 86). Through design thinking, designers empathize with contextual problems to creatively and rationally generate solutions, and through this way of thinking designers are able to better improve their own design process and take innovation to the next level. Understanding the product design process and design thinking are critical to this thesis and discovering how 3DP can be integrated.

Emotional Design

One fundamental aspect of product design is emotional design, which is an element that 3DP and the Maker Movement can directly affect. The emotional side of design may be more critical to a product's success than just its practical elements (Norman, 2004). Norman (2004) identifies three different aspects of design: visceral, behavioral, and reflective. The visceral element is concerned with the aesthetic appearance, while the behavioral factor looks at the pleasure and effectiveness of use. Finally, one's reflective self considers the rationalization and intellectualization of a product. These three levels of human cognizance interact with one another, and design can facilitate finding the proper balance; however, no single product can hope to satisfy everyone, but understanding the designer's audience for whom the product is intended is a step in the right direction. Since a broad and diverse range of individual, cultural, and physical differences exist in the world, creating one perfect product to satisfy all senses is impossible; only a wide variety of products accommodate this spectrum of tastes and preferences. Desires can be dictated by both culture and an individual person. One must also distinguish among an individual's emotional wants and practical needs, as determined by a person's activity. Successful designers therefore must understand that a human want can be just as or even more powerful than a need, and thus must accommodate both in designing an effective product (Norman, 2004).

The element of emotional design that can be one of the most difficult to please is the reflective level, since it evokes a personal satisfaction or memory. Some products may be gaudy aesthetically, such as garish trinkets or souvenirs, but for some these can assume importance as symbols or as a source of cherished memory. This is difficult to design for, as it is hard to create something with the capacity to evoke special feelings. However, objects that we construct ourselves can be the most intimate (Norman, 2004). “Consumers tend to value more highly products in which they have had a hand in their creation, whether assembling a kit or just encouraging the creators themselves online. Researchers call this ‘the IKEA Effect’” (Anderson, 2012, p. 70).

The Ikea Effect

Dan Ariely is a behavioral economist at Duke University who has investigated this “Ikea Effect” in a research paper. This effect reflects the increased value that people attribute to self-assembled or –created products as compared to objectively similar products in which they had no hand in making. He used the example of introducing instant cake mixes in the 1950s. Housewives were initially resistant, complaining that it made cooking too easy, undervaluing their skills and labor. The manufacturers responded to the feedback and responded by changing the recipe to require adding an egg, which resulted in a much more popular and hence more successful product. It appeared that infusing the task with personal labor was an important element in selling the product. Individuals tend to ascribe greater value to the things in which they have labored, which stems from the irony that arduous tasks simultaneously can have rewarding properties (Norton, Mochon, & Ariely, 2011). This finding can help explain the success of product design through 3D printing, and as wise motivation for makers in the Maker Movement (Anderson, 2012).

Personalization and Open Design

Mass production minimizes the possibility of objects having personal meaning. But as manufacturing companies realize this fact, they are beginning to offer customization or special order services and are more likely to provide flexible products that can be tailored to the individual purchaser. However, according to Norman (2004), in order to customize a product successfully for the average person, the choices offered must be made simpler rather than more complicated, otherwise it becomes a daunting task. He suggests that another way to personalize products is to let customers design their own; however, many do not possess the skills nor have time to do this, which is why one of the most feasible ways to personalize a product is to modify an already purchased item. Norman (2004) emphasizes the importance of all of us to think as designers, though we may not be able to design and construct the object itself. However, we can control the products we purchase and decide how we use it, which is the key to personalizing a product. Improving technology and evolving business models may help break down some of these barriers separating companies and the consumer as the former begin to offer products and services that welcome the latter to not only personalize, but also design their own products (Lipson & Kurman, 2012).

As companies and business models continue to evolve, one of the deciding factors predicted to become a major determinant for their success is enhancing the customer's experience and/or involvement in the customization of products, and companies that enable DIY innovation in their products will have a stronger appeal (Gilmore & Pine, 2011). Lipson and Kurman (2012) conceptualize this idea further stating, "3D printing technologies enable us to transcend the mundane, to break out of the realm of commodity products and dull experiences" (Lipson & Kurman, 2012, pg. 51).

Through 3DP and the Maker Movement a new concept of open design in the design process of products has emerged. It has been described as a paradigm shift in which an object to be designed is assigned no fixed identity and instead proceeds through a continuous evolution in which consumers are actively involved in both the design and the fabrication of the product—a radical departure from traditional manufacturing (Van der Beek, 2012). Companies that offer 3DP sharing and printing services have been able to connect with a consumer's need for personalized products and experiences. One example is Shapeways, which is a web-based community marketplace in New York City that serves as the storefront for designers and their 3DP products. It is a platform for personal fabrication that focuses on both the consumer and the designer. Customers may either purchase a product that has already been designed or they can upload their own design and have it printed in up to 25 different printing materials (Kurman & Lipson, 2012). Shapeways now also makes possible for consumers to customize certain products through their website. Consumers can start with a pattern and then increase or decrease the complexity, choose their measurements, add borders, include an engraving, and then select the printing material. By virtue of the new technology this personalized procedure allows non-designers access to the process and the fabrication of their own products.

3D Printing: Design Pedagogy

Gibbs (1988) suggested the pedagogical view of "learning by doing," which comprises phases of action, evaluation, analysis, and reflection in the creative design process. In the process of design an evolution occurs, as a conceptual idea transforms into a physical thing, and more recently the 3DP has been added to the designer's toolkit as a means of not only rapid prototyping, but also as a fabricator of the final product (Fleming and Paterson, 2013). Incorporating these tools along with traditional design tools into the pedagogical design environment and the designer's design process can lead to the emergence of complex form studies as well as elevate the comprehension of the conceptual manipulation of spatial-configurational, physical-behavioral, and material-constructional aspects of design (Sass and Oxman, 2006). 3DP as an iterative design medium embraces the concept of learning by doing. "An important attribute in design is acquisition of processes of redescription or redesign based on acquired knowledge from a previously described artifact—Digital Fabrication offers a new dimension in design learning" (Sass and Oxman, 2006, pg. 335).

> Projects that involve 3D printing both educate and motivate technology students...Being actively involved in a process-model that reflects modern manufacturing methods gives students practice at working together to formulate a solution to a problem or challenge, then follow through from design to prototype to testing. If a particular prototype fails, they can determine why, then go back to the drawing board and try different solutions until they find the right one, just as real-world companies do when producing a product. (Lacey, 2010, pg. 18)

3D Printing: Product Design Process

In the architectural design process practitioners normally explore design possibilities through sketching, hard-line drawings, and physical models (Kroes, 2002). So the idea of physical model making is not new to product design or architecture. Creating representational models help designers realize their mental images as well as envision new forms beyond the initial concept (Sass and Oxman, 2006). The utilization of digital fabricators in product design, however, is more recent. Digital design and fabrication, including 3DP, have the distinct advantage over traditional methods of creating prototypes and final designs in speed. These faster tools, when utilized in the design process, have the additional merit of leading to new inspirations, design ideas, or fabrication techniques that may not have been realized through other, more conventional methods (Sass and Oxman, 2006).

Due to its obvious advantages 3DP has been increasingly used in the development of prototypes and offers more options in materials than traditional choices such as clay, wood, or metal for hand-made prototypes. 3DP can also produce objects with moving parts, utilize multiple materials, and produce prototypes quickly and efficiently (Berman, 2012). "The comparatively high speed and low operational cost of the 3D printers mean that a large number of models can be produced during the product development phase. Designers can go through several iterations having physical samples to evaluate each concept. The models are used to further enhance communication during the design phase, it also helps substantially with error detection" (Miners, 2013). Another advantage of 3DP is its capacity to manufacture high quality material representations for complex designs, and it can support the creative process by replicating variations of single or multiple products at various stages of the design (Sass and Oxman, 2006).

> Digital fabrication for designers offers realistic opportunities for shape representation, evaluation and redesign of complex design initiatives. One asset worth noting is that digital fabrication extends learning in a digital design environment by engaging the designer with materials and machine processes… It may also be said that the use of these appliances and software extends creative design beyond the early stages of design and supports the continuity of design through its various stages. Not only is this an advantage in design, design materialization also has certain didactic advantages that support the acquisition of knowledge and the learning of design procedural structures. (Sass and Oxman, 2006 pg. 334)

3D printing's role in the design process has become more commonplace as it lowers its costs and becomes a more cost-efficient method. As its costs diminish, its ability to produce numerous design iterations from the beginnings stages of the process, as well as its capacity to refine form, fit, and function, makes it a more attractive manufacturing option. (Dimitrov, Schreve, Beer, 2006).

3D Printing: Final Fabricated Product

At present 3DP is experiencing a three-phase evolutionary process. In the first phase, product designers, architects, artists, etc, have primarily utilized 3DP as a means to create prototypes of new designs. The second evolutionary phase of 3DP entails the fabrication of finished goods, which has also been described as 'direct digital manufacturing.' Recent advances in the technology have enabled 3DP to be utilized across a broader range of applications and in a wider range of materials (Berman, 2012). As the technology advances, 3DP has become more productive and economical, and has been incorporated into the mainstream production of such things as orthopedic implants, dental caps and crowns, hearing aids, prosthetic limbs, mechanical parts, jewelry, fashion, as well as, interior products (Lipson & Kurman, 2012). Understanding how to apply 3D printing as a manufacturing tool for finished products also requires familiarity with disparate technical processes such as the printing technique, material use, the binder or binding mechanism, determining nominal dimensions, the building orientation, recognizing geometric features, post-treatment procedures, and infusing the infiltration agent (Dimitrov, Schreve, Beer, 2006).

Knowing the capabilities of 3DP and the various materials it utilizes enables designers to apply it as a manufacturer of products rather than just a builder of simple prototypes. “3D printing is removing barriers of resources and skill that prevented many talented designers from realizing their ideas” (Lipson & Kurman, 2012, pg. 175). Numerous designers have been able to create new and prospering businesses on the Internet through the use of 3DP without the traditional need for up-front investment capital in tooling. Janne Kyttanen, who founded Freedom of Creation, was able to launch his enterprise on the Internet by working through third party companies that had already invested in 3DP technology and were willing to produce small batches of his work (Reeves, 2012). According to Lipson and Kurman (2012), 3DP liberates designers to explore and exploit their creative freedom as well as remain more involved in the more mundane manufacturing process of their finished products.

The third evolutionary phase engages the notion that eventually consumers will own their own 3D printer and will use it to print their own goods. This vision sees future consumers going online to download what they need, and printing it at home, instead of going to the store. The initial focus of this future application is on the less ambitious printing of replacement parts for products or appliances, such as downloading and printing a replacement knob for a gas range (Berman, 2012). Although the technology already exists for the third phase, the general public lack of adequate knowledge and the expense of a desktop 3D printer have limited the number of households that currently have a 3D printer. Nevertheless predictions assert that 3DP use will increase as affordability, usability, and reliability improve (Reeves, 2012). 3D Systems, a manufacturer of 3D printers, for instance, reported that between 2010 and 2011 the revenue from sales of mid- and small-sized personal and professional-grade 3D printers increased approximately 40 percent over the previous year. Nonetheless conflicting views project that most consumers will never own or operate a 3D printer, but instead will depend on a service such as Shapeways to produce their products (Lipson & Kurman, 2012). Only time will tell. After all, no could have imagined the popularity of personal computers.

Conclusion

A review of literature suggests that Maker Movement and 3DP have the potential to make a real-world, positive societal impact on product design and fabrication as they inspire and create a new breed of makers and entrepreneurs. Individuals today have the capacity and wherewithal to drive a product's design and fabrication, and 3DP and local tech shops enable their localized production. These tech shops have facilitated the attractive and potentially ultra-effective concept to design globally, produce locally. Incorporating these visions and tools into design education with an emphasis on their application in the design process of interior products could encourage and inspire students to become a part of the Maker Movement and to use 3DP, as the fabrication method has promise, despite growing pains, flaws, and shortcomings, to become a key element in the design process of the future.

CHAPTER III

METHODOLOGY

The methodology devised for this thesis is defined by three distinct phases that investigate the role of 3DP in the design process through applied creative explorations of interior products. In Phase I, I focused on a research project exploring 3DP as an iterative design tool in product design. In Phase II, I collaborated with a fellow graduate student to explore 3DP in the design process and as a final fabrication method for a furniture prototype. Finally in Phase III I facilitated a 3DP Product Design Workshop, in which undergraduate students were asked to improve upon an existing product in an interior environment by incorporating 3DP into their design process. As a resource for students' use in the workshop, I developed a set of 3DP guidelines (see Appendix B) that aimed to provide a critical overview of 3DP and how to incorporate it in the design process. These guidelines were informed by my 3DP design experiences from the first two phases of the methodology as well as from my review of literature. It is expected that each phase of the methodology adds to the body of knowledge on the evolving technology of 3DP and contributes to a critical understanding of the impact of this technology on designers and makers in their design and fabrication endeavors.

Phase I

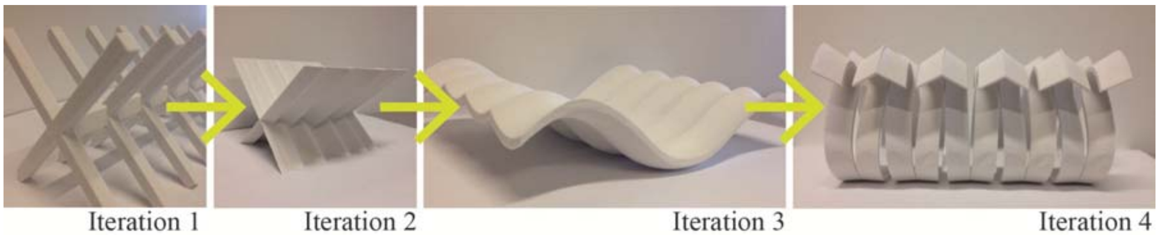


Figure 2. One Part of the 3DP Iterative Design Project

An important goal of this thesis is to gain first-hand experience and critical understanding of the capabilities of 3DP application in the product design process. Through creative exploration conducted in a studio class, I investigated 3DP as an iterative design tool. The project aimed at investigating how 3DP would affect the design process as I integrated design thinking through each stage of analysis and synthesis in the design process. In this phase I produced 32 products in 32 days through the course of four stages, in which the 3D printer was used as a means to iterate, design, and fabricate a new product every day. The project was constructed to explore 3DP as a means to facilitate the realization of new viable products; as an enabler of rapid ideation; as a link between conceptual design and its physical realization; and as a means to illustrate new opportunities in the representation, evolution, and redesign of a complex form.

The Design Process

To begin, in order to investigate how 3DP would affect the design process through this iterative design continuum, it is important to understand the product design process as well as to know how design and fine art are different especially in the context of this project. Design can be defined as the act of making, whether a drawing or product, to express or represent an idea that implies desire, creation, function, fit, and purpose (Poldma, 2009). To further elaborate,

> Design is….the ability to imagine that-which-does-not-yet-exist, to make it appear in concrete form as a new, purposeful addition to the real world…things that really count, and are highly valued, come from design, when not directly from nature (Nelson & Stolterman, 2003, pg. 10).

Design is artistic and creative, yet functional and practical, since it is the task of designers to create new possibilities that allow people to experience a product or a space with a function in mind. Design can often be mistaken for art or creative innovation. Although design incorporates elements of innovation and creativity, design must respect certain parameters that distinguish it.

> The thing which sharply distinguishes useful design from such arts as painting and sculpture is that the practitioner of design has limits set upon his freedom of choice. A painter can choose any imaginable shape. A designer cannot. If the designer is designing a bread knife it must have a cutting edge and a handle…These are the limitations that arise, as anyone can tell, from the "function" of the thing being designed (Pye, 1978, pg. 11).

In the design process (see Figure 7), designers go through a process of analysis and synthesis by following a sequence of steps in order to guide a design from an idea to a reality. Designers begin with a problem or situation that must be resolved through thought and exploration. Research or data collection is then implemented, which allows the designer to analyze the various methods that could be used to creatively solve the problem at hand. Conceptual development then occurs to ideate solutions. After synthesizing various ideas and possibilities, the designer selects one and then evaluates it to determine what works for the given project. The whole process or certain steps of it can be repeated in order to develop a final conceptualized design solution that encompasses an analyzed, synthesized, and tangible design (Poldma, 2009).

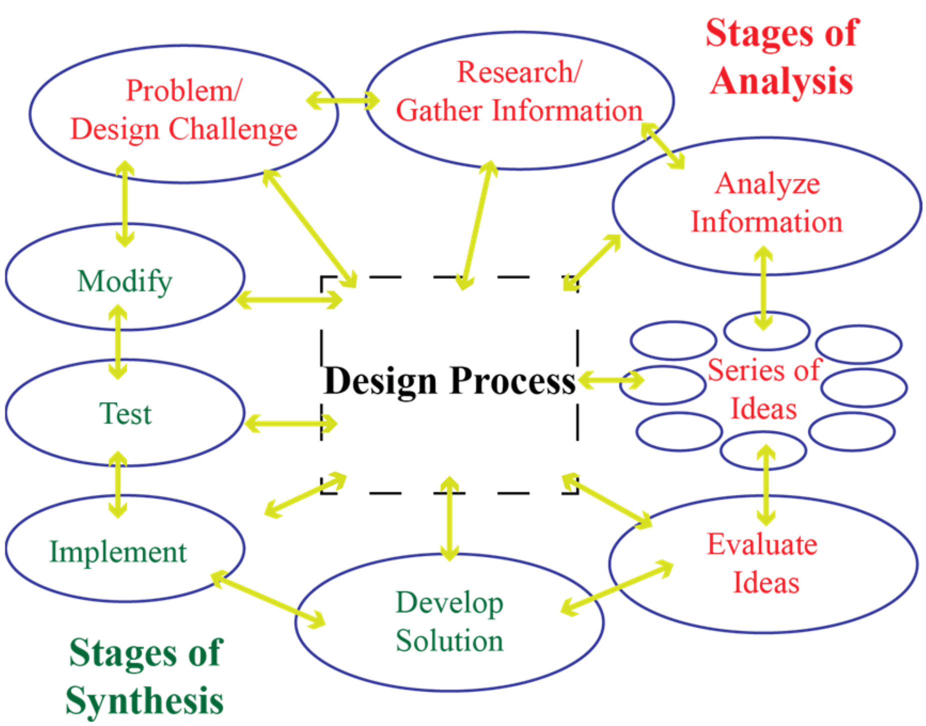


Figure 3. Traditional Design Process (Poldma, 2009)

In this iterative design project, I focused on how each new iteration could be conceptualized and realized through 3DP. Although each product went through an analysis-synthesis design progression, the project as a whole evolved through a design process applying 3DP and iterative design. 3DP enabled the stages of analysis and synthesis to be simultaneously intertwined throughout the design process rather than as sequential steps (see Figure 8). Through 3DP, I was able to go from idea to reality quickly and efficiently, as each product was designed and developed through rapid prototyping, which suggested and contributed possibilities during the course of the entire project. This type of iterative design process was made possible by using 3DP technology. Through each 3D printed iteration, I was able to investigate design problems arising from the product's form and function, and as I proceeded, incorporate a design-thinking process to explore new design possibilities. The results discussed in this chapter illustrate successes and failures in product design and the use of 3DP as a tool and as a fabrication method in the design process. These findings enabled me to explore a body of work that intersects design, technology, and art, as well as acquire a critical understanding of 3DP and interior product design.

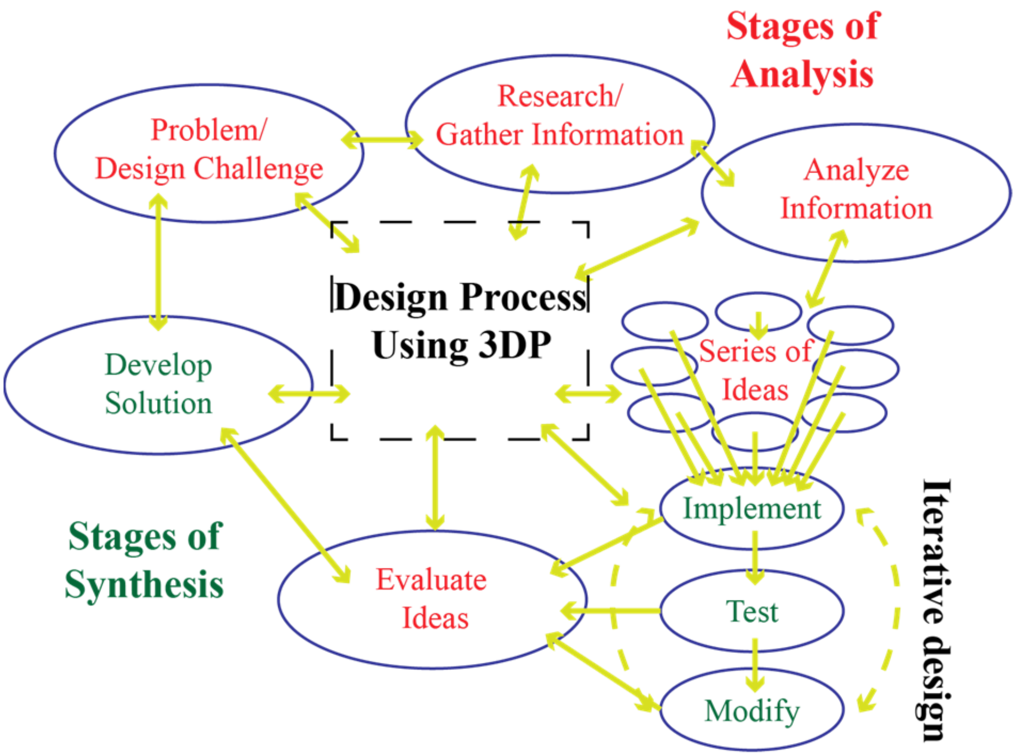


Figure 4. Design Process using 3DP

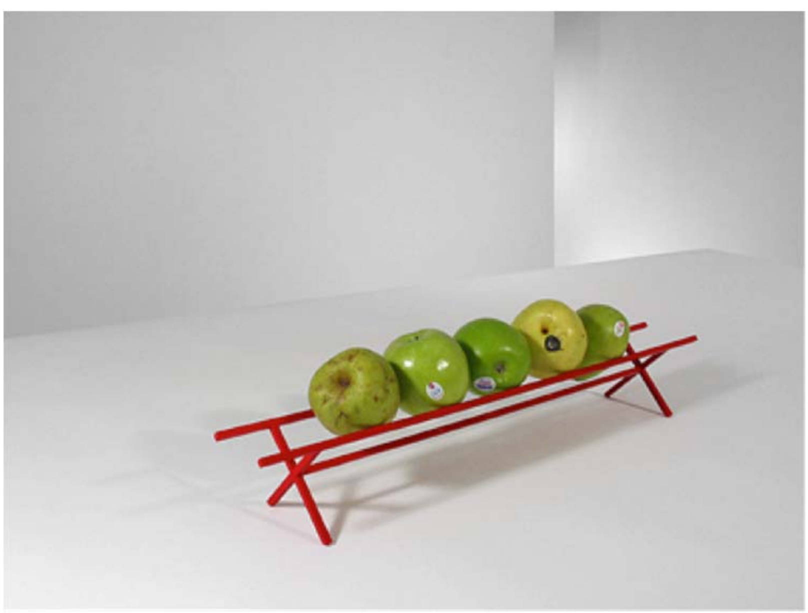


Figure 5. Precedent: Fruit Bowl No. 5 by Ron Gilad

A contemporary product, Fruit Bowl No. 5 by Ron Gilad, was selected as a precedent and baseline to begin the iterative design process. The precedent was chosen based on its unique form that could easily be manipulated by the ordering principles of design, which were used as a guide in each phase of the iterative design process. The painted metal precedent, which measures 23 inches long, 4 inches wide, and 3.75 inches tall functions as a fruit bowl that holds medium to large sized fruit such as apples or oranges. Gilad used deconstruction and reduction as a conceptual driving force throughout his product design process. This minimalist design incorporates solids and voids to reduce the support surface thus creating a fruit stand rather than a fruit bowl. My aim in this project was to digitally modify and manipulate the current design through the ordering principles of design to increase the type and amount of fruit the vessel could hold in the first three stages of the project. In the last stage, the iterations were transformed as directed by the design of the previous iterations through the principle of transformation. Each new product was evaluated using a qualitative product evaluation sheet that I designed (see Appendix A). The products were evaluated by the level of deviation and evolution from the preceding iteration; the use of 3DP as the fabrication and ideation method; and the success of the functionality and viability of the new product.

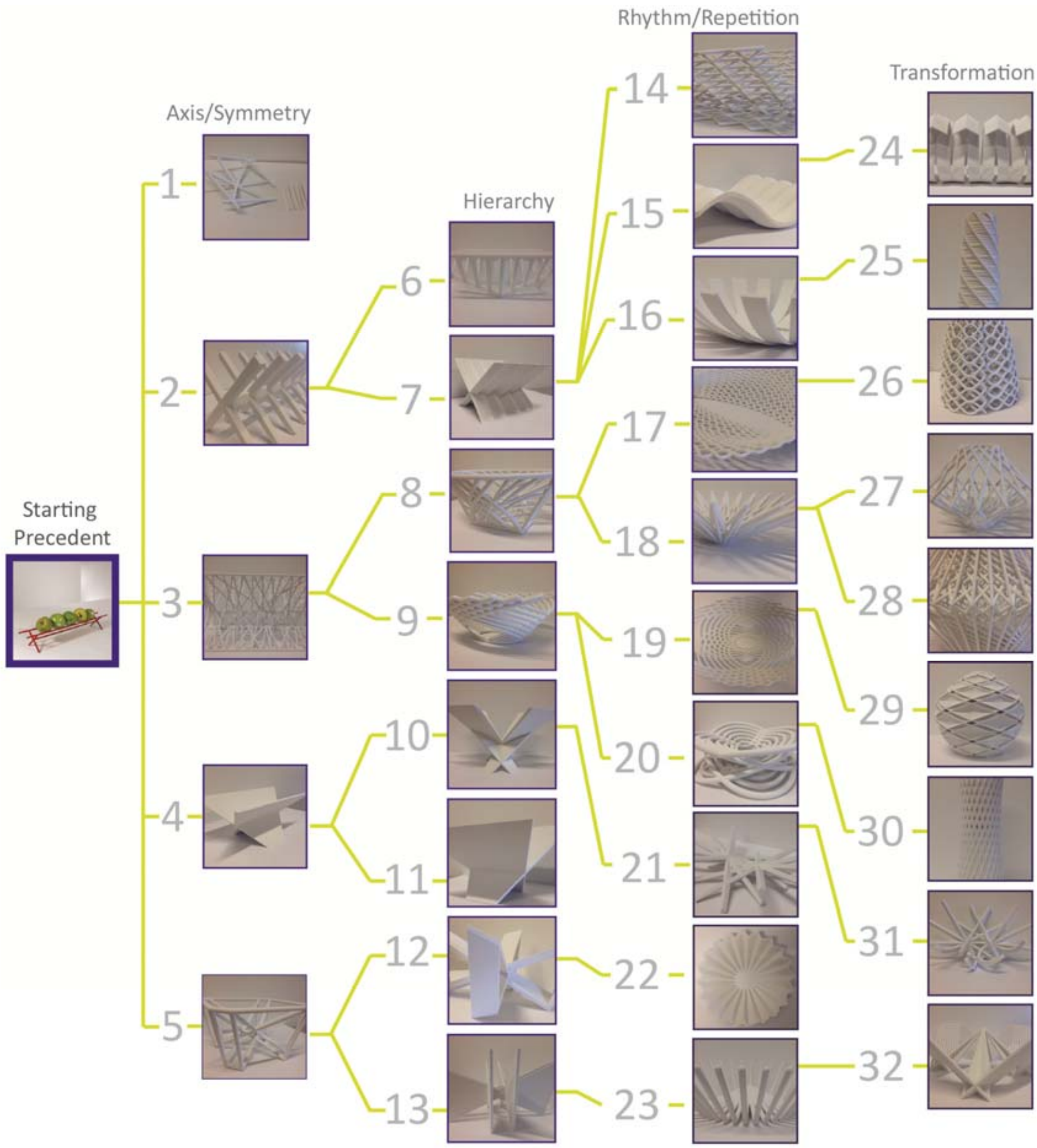


Figure 6. 3DP Iterative Design Project. 32 Products in 32 Days

Phase II

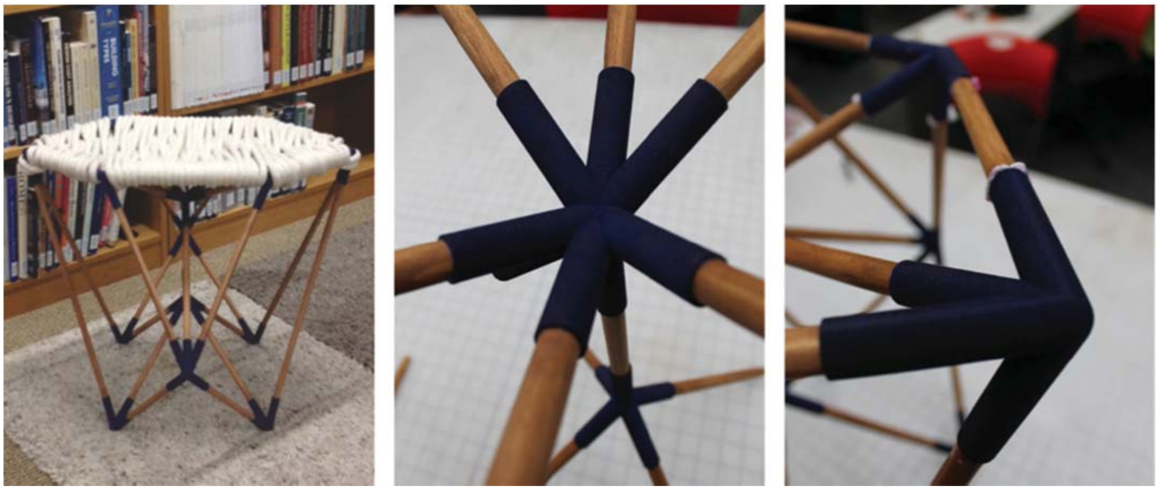


Figure 7. Final Prototype and 3DP Printed Component Details

In the second phase I worked with a graduate student partner in a collaborative applied creative research project. This enterprise utilized 3DP not only as an implement in the design process, but also as a means to fabricate elements in a full-scale furniture prototype. This phase proposed to expand upon the knowledge learned in the first phase project beyond its implementation as an iterative design tool. 3DP was used in this phase of the design process to develop concept models, to test parts, to test various materials and their properties, and to generate scaled process and design development models. Phase II also investigated how designers and makers could utilize third party printing services such as Shapeways, and how 3DP could manufacture components in the final fabrication of a full-scale prototype.

3DP conceptual models in Gypsum powder.

Scaled model with 3DP Gypsum powder joints and dowels.

Full-scale test joints in various thicknesses in ABS plastic and SLS nylon.

Final pre-dyed 3DP joints in SLS nylon.

Figure 8. Images of 3DP in the Design Process of Phase II

In collaboration with a fellow graduate student with considerable experience in woodworking, the project started with the goal of integrating 3DP with conventional construction materials and methods in building a stool for UNCG's Department of Interior Architecture's library. 3DP was utilized in the early stages of the design project as a means to produce physical representations of various iterations of initial concepts, which were printed using a z-corp gypsum powder 3D printer. Once a design concept materialized and it was decided how 3DP would be incorporated into the final design, scaled and full-scale model connectors were printed to test the fit, form, and function. Three different materials were tested to compare their structural and physical behaviors—gypsum powder, ABS plastic, and SLS nylon. After testing the structural strength of each material, we were able to print the final full-scale connectors in SLS nylon through Shapeways. This 3D print was used in the final full-scale stool prototype. Overall the stool was successful in both function and design. Further iterations would be tested and examined in the interest of strengthening the structural system and reducing the cost of 3D printed components.

Because the first phase of the project evaluated 3DP as a tool in an iterative design process using a local gypsum powder 3D printer, the second phase explored the design process from the initial concept to the final full-scale prototype utilizing multiple materials and a third-party printing service. Both phases of the project were vital in understanding how 3DP could be incorporated into both the design process and the development of the 3DP guidelines (see Appendix B) that were subsequently integrated as a resource in the third 3DP workshop phase.

Phase III

The third phase of the methodology entailed conducting a 3DP Product Design Workshop. This workshop was conducted in a classroom environment in the form of a pilot study to test the use of 3DP in the product design process of undergraduate students. The results of the study would be used to evaluate how design students with little to no 3DP experience incorporate 3DP into the design process. Students were supplied with various educational resources in order to ascertain whether one resource was a more effective teaching tool. As a secondary purpose of the workshop, the participating students evaluated the guidelines on 3DP as effective or ineffective instruments in informing their work.

The 3DP product design workshop encouraged students to integrate 3DP into the design process and fabrication of an innovative interior product of their choice that made everyday living better. As makers in the Maker Movement tend to focus on problem solving through design and fabrication, the students were to improve upon and/or redesign an existing product in an interior environment. This product was to be no larger than approximately 4” x 4” x 4” to allow students to print multiple products immediately on the locally available 3D printer. There were thirteen students in the workshop, and they were randomly divided into three distinct groups: the first group of four students received both the 3DP guidelines, and the lecture and demonstration on utilizing the 3D printer; the second group of five students received only the 3DP guidelines; and the third group of four students had the lecture and demonstration on utilizing the 3D printer. Although separated into groups, students worked on the project independently over the course of two-weeks. The students were permitted to use a 3D modeling software of choice for their design and fabrication. Students were also encouraged to utilize both 3D printers available on campus—z-corp gypsum powder 3D printer in the computer lab in the Department of Interior Architecture department and a MakerBot Replicator II in the university library that prints in ABS plastic.

The project began by distributing the design opportunity to the students, which specified the design parameters and the overall timeline of the project. Following a brief discussion of the project, a short video produced by Shapeways was played on the benefits and application of 3D Printing. The students were given half an hour of class time to start researching and brainstorming. Finally, the students were placed in one of the three groups, according to the alphabetical order of their names on the class roster. The second group, which received only the guidelines, was asked to continue the project outside of class. Groups 1 and 3 received a short lecture and demonstration on how to utilize 3DP in the design process as well as some important suggestions in preparing a model for 3DP. The content in both the 3DP guidelines and the lecture and demonstration were similar, but how the information was delivered to the students was different.

During the next meeting students discussed their design concept. They identified precedents and shared concept models or sketches of their product ideas. Examples of product ideas include mugs that incorporated a tea bag holder, new modular shelving units, jewelry organizer and holder, and a new compartmentalized vase for flowers. Each student received feedback on their ideas and suggestions on improving their products. In the following class the students were expected to give interim presentations with 3D printed scaled models of their products. Due to long wait time to access the 3D printer in the university library and unforeseen 3D modeling issues, only four students had models to present. These students explained the design concept behind their product., the product's function, design details, how 3DP was utilized in their process, and any additional successes and failures regarding 3DP and their product. The 3D printed models revealed scale and proportion issues; usability concerns; modeling limitations; and fit, form, and function problems. Such issues could be expected for these early efforts with this new medium. The presenters were evaluated by their group peers through a peer evaluation sheet developed for this stage of the workshop. The questionnaire rated students both qualitatively (written comments) and quantitatively (numerical ranking measured on a 5-point scale) on clarity of concept, ability to resolve a problem, ability to visualize design, and the use of 3DP in the design process.

The final project presentation followed a workday, when the students continued to develop their products and seek feedback on their scale models. In the final presentation, students presented and discussed their 3D printed product prototype. They explained their product concept, mentioned problems solved, and their overall 3DP design process. Final products included an innovative wall mounted covered toothbrush holder, a spherical sound amplifier for cell phones or ipods, an easy storage travel shelf/box, and a flower vessel design assistant. The presenters were evaluated again by peer students in their group. All the students filled out a self-evaluation questionnaire (See Appendix C) on their products, reflecting on what they learned in the project, how 3DP affected their design process and final product, and suggestions on changes to the guidelines and other provided resources.

In order to assess how the students utilized 3DP in their product design process and how the varying resources given to each group affected the results, I analyzed the student questionnaires based on the qualitative and quantitative remarks as well as their final product outcome. Through the work of a small sample group of design students, the workshop provided valuable information on the use of 3DP by the students in their design process, as is discussed in the next chapter.

CHAPTER IV

ANALYSIS

This analysis discusses the results from each phase of the study. The research combines intuitive, experimental, rational, and analytical methods in each phase to investigate the role of 3DP in the design process. Through exploring, experiencing, and documenting the successes and failures of 3DP in different design settings, this project sheds light on its suitability in the design process.

Phase I

In the first phase, I investigated the use of 3DP in the design process through an applied creative research project. The purpose of the project was to explore and identify the capabilities and constraints of 3DP as a tool for iteration in the product design process. The results from this phase were then applied to the overall thesis research regarding the impact of 3DP on the design process. The resulting experiences and knowledge acquired in Phase I were also incorporated into the 3DP guidelines subsequently provided to the students in the 3DP Product Design Workshop as a primer on how to utilize 3DP in the design process.

Phase I focused on the role of 3DP in the design process and investigated how 3DP could be integrated as an iterative design tool. The applied aspect of the research project examined the impact of 3DP in the design and creative fabrication of a vessel.

The aim of the research was to explore how design iterations, based on select principles of design, functioned as elements of change leading to new, innovative products. I incorporated Francis D.K. Ching's "Ordering Principles of Design" as described in *Architecture: Form, Space, and Order* (1996) as elements of change at each level of the iterative design process. Ching's specific design principles were Axis and Symmetry, Hierarchy, Rhythm and Repetition, and Transformation. The project began with the selection of a contemporary precedent, Fruit Bowl No. 5 by Ron Gilad that henceforth provided the starting point for the iterative design project. The precedent's design is a unique and modern interpretation of a fruit bowl. Aesthetically the design is appealing with its minimalist structure and straight lines. However, the design limits the type and amount of fruit the vessel can hold due to its existing solids and voids. I took this particular design constraint into consideration in order to improve upon the design while at the same time examining new product possibilities.

Proceeding from the precedent as a baseline, modifications were made through daily-fabricated iterations based on one of Ching's design principle. Each new product was evaluated and analyzed according to the product's functional viability, its structural integrity and feasibility, the particular design principle utilized in the iteration, and the application of 3D printing as a design ideation and fabrication tool. In short, Phase I linked conceptual designing to real world manufacturing through 3DP. This first phase also investigated the suitability of 3DP as an iterative design tool. Concurrently it demonstrated how a design could progress from conceptualization to fabrication in as short a span as 24 hours through 3DP and how the process could rapidly generate new products using 3DP to visually review each possibility in the representation, evolution, and redesign of the product in question. Throughout the 3DP design process, I experimented with possible iterations that were essentially deviations from the original product as generated by applying specific principles of design. Through the project's first three process levels, the original function of the precedent Fruit Bowl No. 5 was maintained, but eventually the function was modified in the last level of Transformation. The viability of each transformed product was judged by the design, scale, proportion, complexity, and overall form and function.

Another notable aspect of this project is to take note of the tools used to create each iteration. I used Rhino 3D modeling software in which I have three years of experience working to digitally model the iterations and each iteration was printed using a z-corp gypsum powder 3D printer. This material is practical for prototyping as it is less expensive than other available materials such as plastic and can illustrate detail fairly well. However, the material can be fragile and brittle, so structural integrity was a concern throughout the design process as I 3D modeled and printed each product. Also, although this printer can print in color, for consistency purposes and the fact that color was not one of the design parameters, each iteration was printed using the natural white color of the gypsum powder. The aim was to use the gypsum powder material to explore how I could use 3DP as an iterative design tool in the design process, with the intention that final products could be further investigated using other 3DP materials. This chapter presents the results from each stage of the design process.

Axis and Symmetry

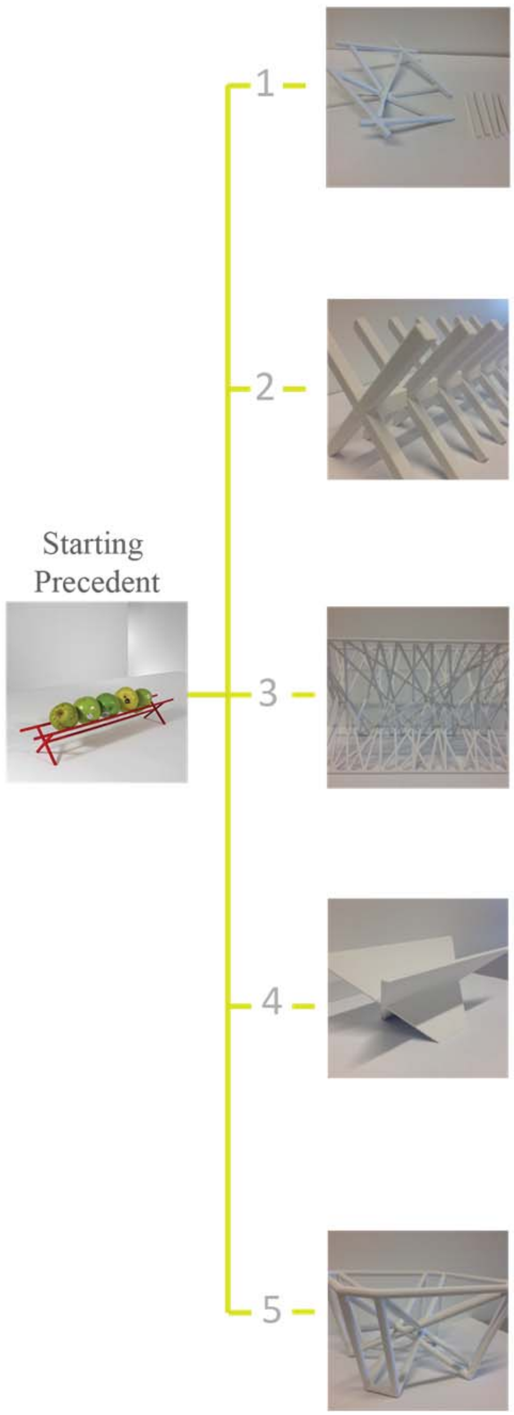


Figure 9. Product Design Iterations based on Axis and Symmetry

The first principles analyzed were Axis and Symmetry, according to which I created five iterations based on the starting precedent. Axis is defined by a line established by two points in space about which forms and spaces can be arranged. Symmetry is the balanced distribution of equivalent forms and spaces about a common axis or center (Ching, 1996). This stage of the iterative design process revealed both successes and failures.

Product 1

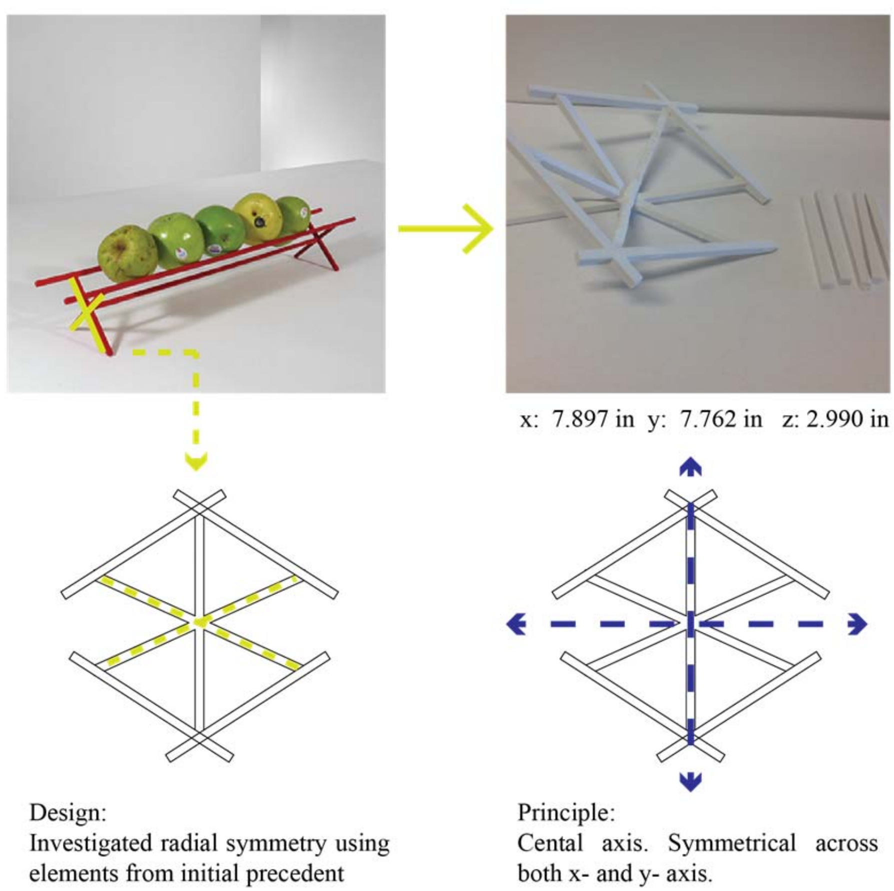
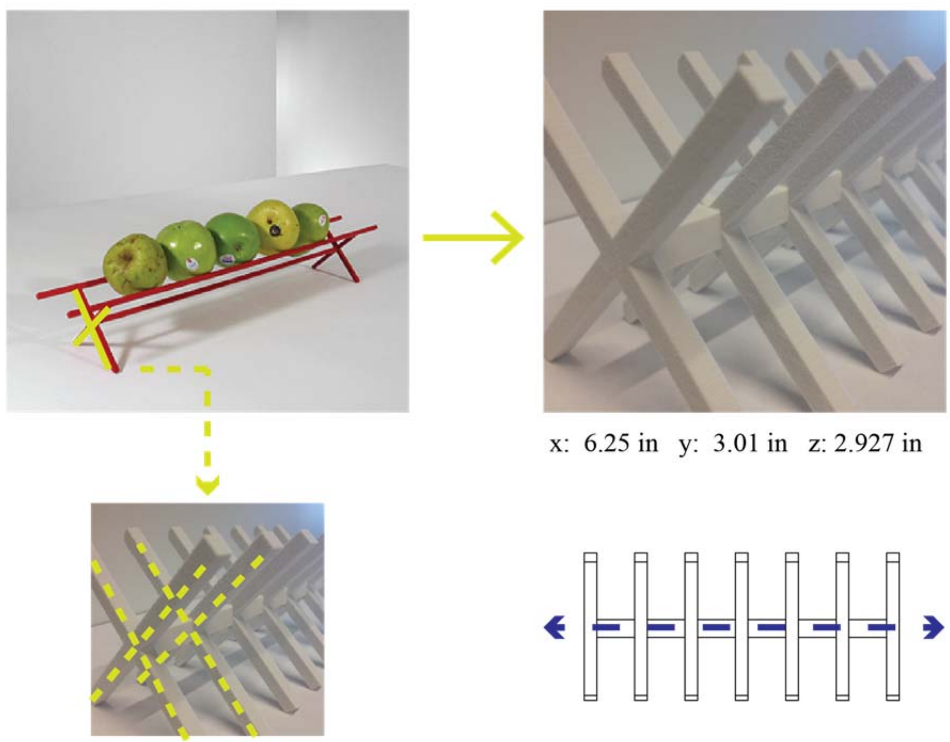


Figure 10. Product 1 Design Process

I analyzed the form of the starting precedent for the first iteration using radial symmetry. The simple lines of the precedent effectively enabled the vessel to hold larger fruit such as apples and oranges. After analyzing the shape and elements of the precedent, I conceptualized how I could refine the form through the ordering principles of design: Axis and Symmetry. I defined my iteration objectives as wanting to create a new design that continued to define axis and symmetry through a new form as well as to enable the vessel to hold even smaller fruits such as lemons and limes. With this new design I hoped to expand the types of fruit that the vessel could hold. Using commands in Rhino, such as Line, Surface, Extrude Surface, and Rotate, the new iteration kept similar lines and angles, but created a center point at which the elements could intersect, thus illustrating radial symmetry around a center point. The design concept was implemented and visualized digitally; it was then 3D printed to test the results within 24 hours of starting the design process. Although visually pleasing, the physical product was not structurally viable to support all of its elements, and broke due to the disproportionate weight above and below the central point. Although this product was not structurally sound, I was able to analyze and evaluate the viability of the product's function. I realized through testing the physical product that the vessel was too small, and despite the fact that the vessel could now hold smaller fruit, it lacked the versatility to hold larger pieces of fruit. Overall, the design principles were well defined, but the use of 3DP enabled me to analyze the failures of this product's design as well as discover the drawbacks of using 3DP as a fabrication method for this item. I was able to learn from the issues of scale, proportion, and overall form quickly in order to improve on the next iteration. Due to design and concept failures, I chose not to continue with Product 1 for the next level of iterations. However, addressing the failures such as the structural and scale issues would be informative to future iterations.

Product 2



Design:
Investigated bilateral symmetry through repeated base element from original precedent.

Principle:
Cental axis. Symmetrical across and y- axis.

Figure 11. Product 2 Design Process

In the next iteration, I continued to deviate from the initial precedent with the similar goal of functionally expanding on the types and amount of fruit the vessel could hold, while still applying the design principles of axis and symmetry. I continued my design process by exploring other design concepts digitally that could result in an acceptable solution. In this iteration, I used Rhino modeling commands Line, Surface, Extrude Surface, Rotate 3D, and Array to experiment with keeping a similar form of the original. However, I removed the top bar elements of the item and replicated the base along the central axis as the means to hold the fruit contents. This design solution utilized bilateral symmetry while still emphasizing the design principles of axis and symmetry. In this design, I hoped to vary the types of fruit the vessel could hold by limiting the spaces between the openings; however, after analyzing and testing the 3D printed product, I discovered that the vessel was too long in length to its width and height to be successfully functional. This design result was also not as attractive aesthetically, since it lacked innovative qualities and the design uniqueness prominent in the precedent. The use of 3DP as a fabrication method proved beneficial at this stage, as no additional assembly was required to test and evaluate the product; however, the lack of complexity in this resulting form did not take full advantage of 3DP as a fabrication method. Saving on experimental time and fabricating complex structures are two principal advantages of 3DP. Through the use of 3DP in the design process, I was able to test the scale, proportion, and function of the product.

Product 3

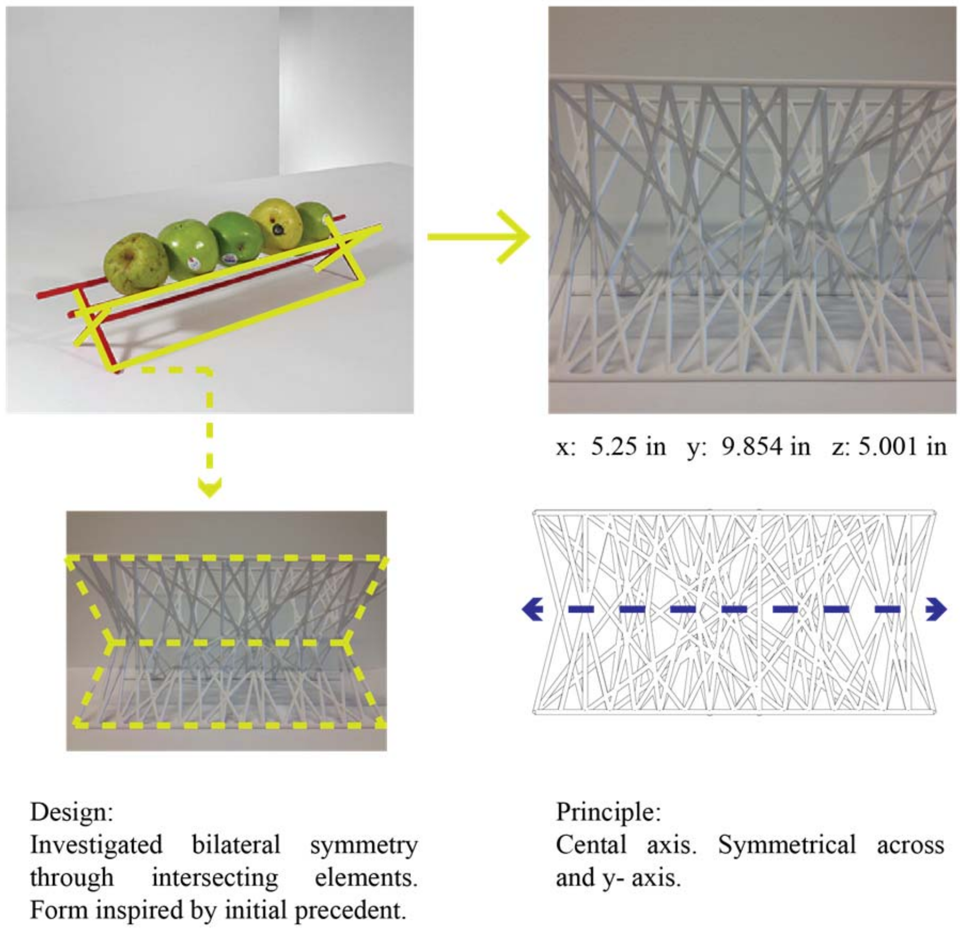
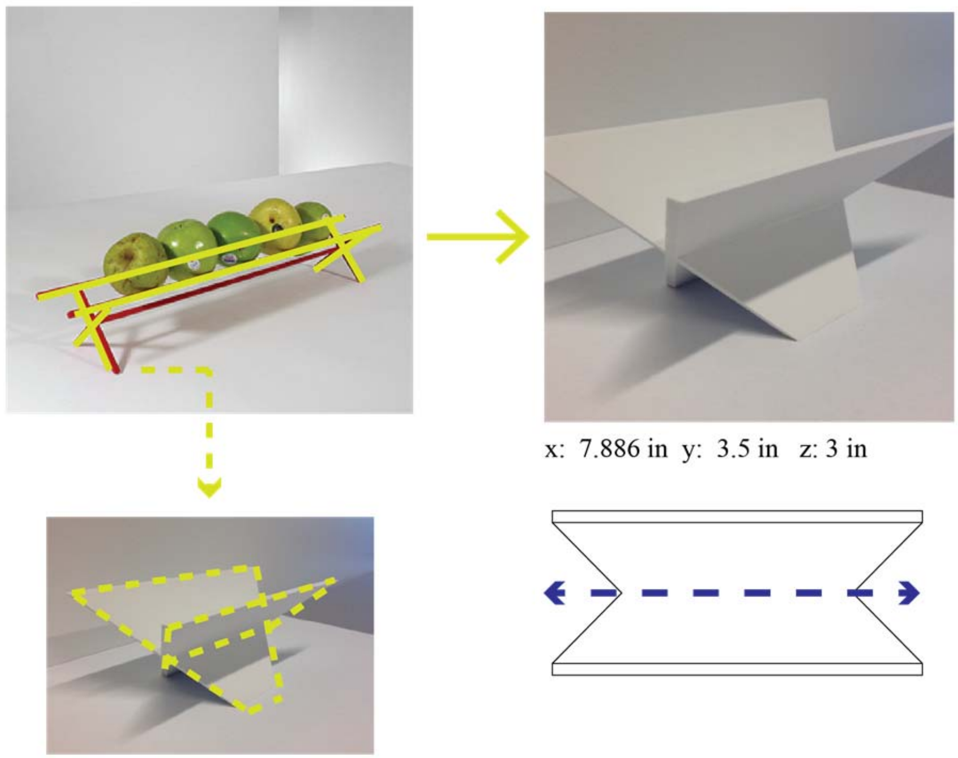


Figure 12. Product 3 Design Process

Continuing this project, based on the initial precedent and the design principles of axis and symmetry, I incorporated my reflections and results from the previous iteration into the next product’s design. I continued following the design criteria I hoped to apply to this product—increase the viable functionality of the vessel through an innovative and complex design and utilize 3DP as a fabrication method. In this iteration I used the commands Line and Pipe to increase the overall scale of the product and continued with the overall shape of the precedent’s design.   However, I explored axis and symmetry through the intersection of the individual elements that defined the overall product. The elements were designed to intersect each other seamlessly with little space between; this would create an understood axis and an intricate design that would have been difficult to fabricate as quickly using other methods of fabrication.   After 3D printing the new design, the next step in the design process was to evaluate the product’s viability, the effectiveness of 3DP, and how well it illustrated the stated principles of design. This iteration was more successful functionally, as the increased size and spacing between the elements of the product enabled a wider variety of fruit to be held in the vessel. The product’s complex design and lack of additional assembly demonstrated 3DP as an effective fabrication method.. The structural integrity of the 3D printed product, however, was not as successful; the individual elements tested brittle due to their thin wall thickness. Nevertheless, this 3DP product iteration provided another important learning experience. This design also needed further investigation. Although it was more functional, the intersecting elements needed more purpose than narrowing the spacing, such as specifically being spaced to hold a lemon or a lime. Analysis of the printed product revealed that the product required further design and conceptualization before it met requirements for success. Working on this product exemplified how a design, although functional, was still not entirely successful when other elements such as concept and structure were not as adequate.

Product 4



Design:
Investigated bilateral symmetry through planes. Form inspired by initial precedent.

Principle:
Cental axis. Symmetrical across and y- axis.

Figure 13. Product 4 Design Process

In the next iteration, I launched the design process by contemplating other, yet unexplored way to modify the original precedent to increase its functionality and purpose. In the previous iterations, I focused mainly on manipulating the current elements of the precedent's design to improve the product. In this design I investigated the geometric form through planes rather than lines using the Rhino commands Line, Surface, Loft, and Mirror. This solution would address the problem of increasing the type and number of fruit the vessel could hold by eliminating the voids in the original design. After applying 3DP to the product, it became evident that although the vessel illustrated axis and symmetry clearly, it was too small, and the size of the planes above the axis were not long enough for the new design to be functional as vessel holding fruit of various sizes. Although the design was geometrically simple and interpreted the precedent well, it did not push the capabilities of 3DP as a fabrication method to its optimum. In reflecting on Product 4, as with earlier models, further iterations needed to be explored in order for the product to be successful.

Product 5

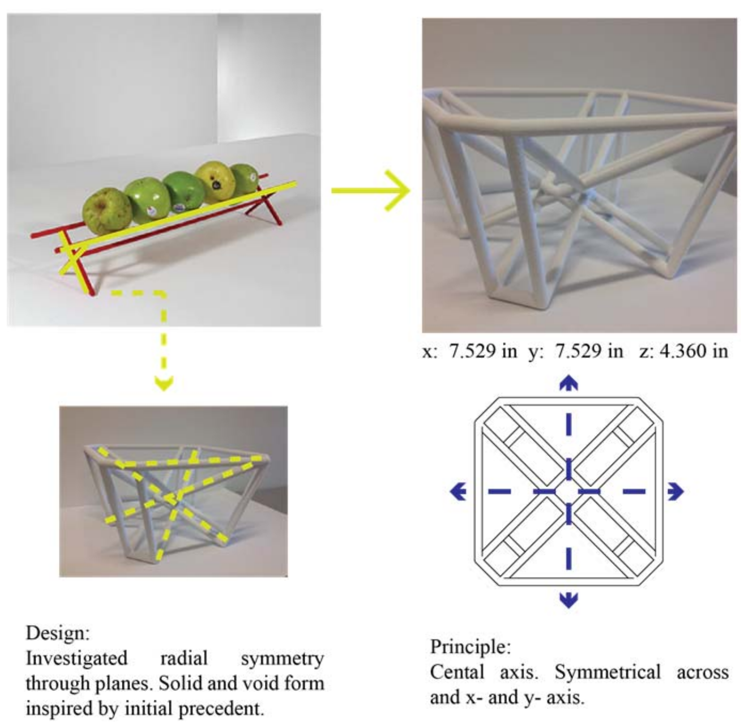


Figure 14. Product 5 Design Process

In the final iteration of the initial precedent, still focusing on integrating the principles of axis and symmetry, I explored altering the form by using radial symmetry. Since the first model of this iterative design project illustrated radial symmetry, but was not structurally viable, my hope was to explore a new possibility that would be more durable. The design used the Rhino commands Line, Rotate, and Pipe and aimed to interpret the initial precedent based on its lines and angles, but through a new form that emphasized radial symmetry. In this design step, I used 3DP to analyze and critique the viability of this product functionally and aesthetically. The scale of the product was more appropriate as compared to earlier iterations, and radial symmetry was successfully illustrated. But the shape, the solids, and voids of the product, which I was able to test with the 3D printed product, still limited its functionality as a vessel that could contain multiple varieties of fruit.

Conclusion: Axis and Symmetry

Through this section of the iterative design project, I determined that none of the modified products were developed well enough to be truly successful. But through the analysis and evaluation of each printed model resulting from the design process, I was able to conceive further design possibilities and was able to continue to seek satisfactory design solutions. In terms of analyzing the use of 3DP as a fabrication and ideation instrument, each iteration benefited from the fact that no additional assembly was required after the product was printed, allowing for me to analyze and iterate the next model quickly. However, I discovered that 3DP has the unique technological ability to create forms that cannot be produced through most other fabrication methods. I also realized that most of the iterations in this stage of my experimentation did not utilize this advantage fully. Thereby one may conclude that 3DP was not always the best choice as a final fabrication method for every product. Despite this revelation, this technology allowed me to speculate on how to improve each subsequent design based on the strengths and weaknesses in design, function, and viability of the previous iterations. These weaknesses and strengths were also revealed through the physical 3D printed models and analyzed using daily evaluation sheets (see Appendix A). In conclusion, 3DP enabled me to incorporate stages of analysis and synthesis (see Figure 8) throughout the design process of each product. The results from this stage of the project would also serve to generate the next set of iterations according to the next ordering principle of design.

Hierarchy

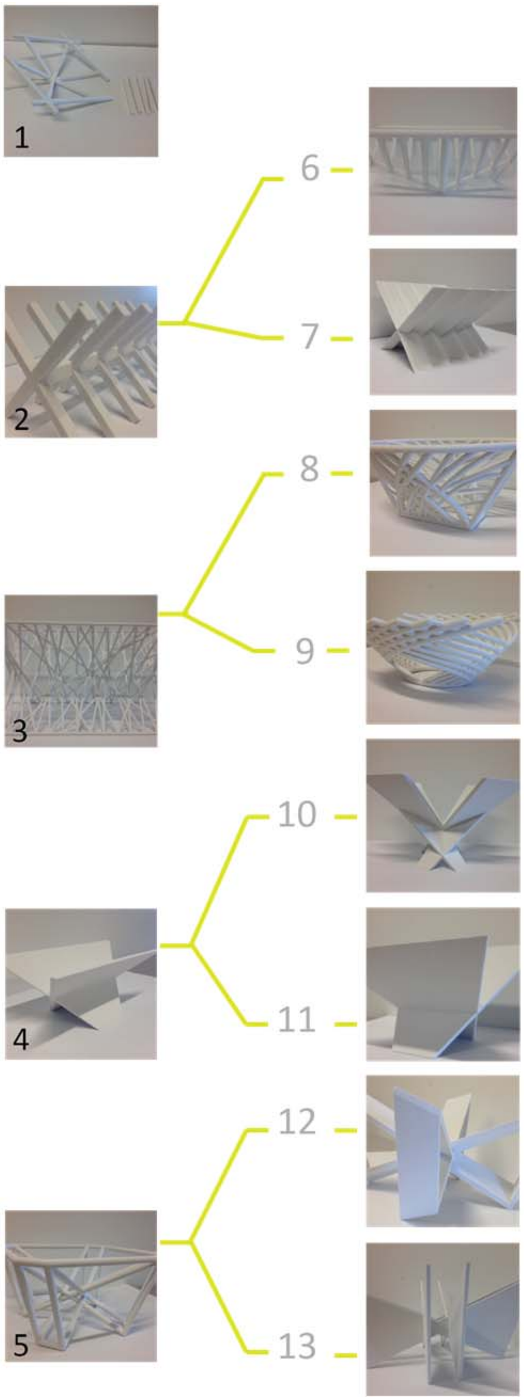


Figure 15. Product Design Iterations based on Hierarchy

At stage two of the iterative design project, I utilized Ching's (1996) Ordering Principle of Design, Hierarchy. Hierarchy is the articulation of the importance or significance of a form or space by its size, shape, or placement, relative to the other forms and spaces of the organization (Ching, 1996). The previous level's results identified five vessel iterations. As noted earlier, after analyzing the first group of iterations based on Axis and Symmetry, it was determined that the first iteration would not be explored further due to the lack of structural integrity of the product. The next set of iterations, based on the guiding principle of Hierarchy, were generated from products 2-5. Each new iteration attempted to improve upon the previous ones while incorporating Hierarchy into the new design.

Product 6

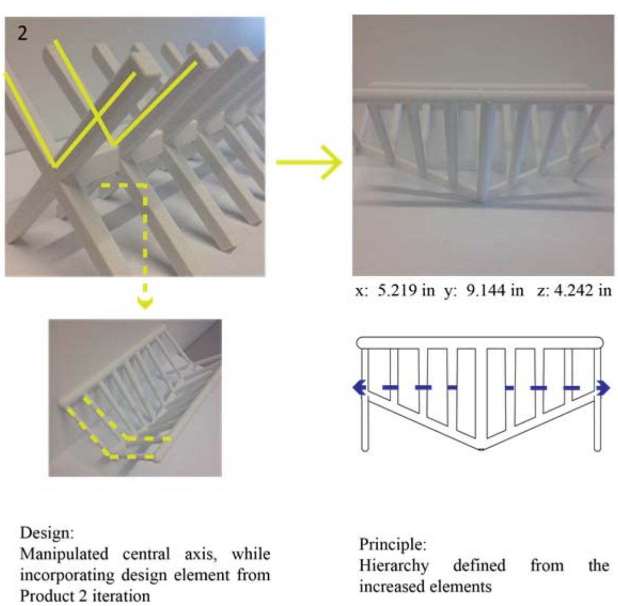


Figure 16. Product 6 Design Process

In this first iteration applying the hierarchy principle, I focused on evolving the design of Product 2. I started the design process of this iteration by identifying the design problems of Product 2, and establishing the design objectives for the new form. With the intent to still develop a vessel to hold fruit, I hoped to increase the functionality, increase the design integrity, and illustrate hierarchy in this iteration. I then used the Rhino commands Line, Surface, Extrude Surface, Offset, and Pipe to digitally design a model that manipulated the central axis while maintaining similar design elements from Product 2. The basic form had a central focal point at which the design elements decreased in diameter and length from the inside to the outside, which could be used to illustrate the principal of hierarchy. Unfortunately the 3D printed product revealed significant design and structural flaws in the design. The legs were not strong enough to support the overall product, and the lack of creativity in the design was clear in the physical printing. The scale and proportion of the product, however, satisfied the design requirements as a vessel for holding fruit. But this was the only point of success in this product. Although featuring 3DP in my design process facilitated giving concrete form to an idea thus aiding quick and effective visual analysis, the result was unsatisfactory. Through fashioning this product by virtue of 3DP, it was evident that this iteration was aesthetically unappealing, structurally unsound, and even economically it was a more expensive creation to print as it used more material.

Product 7

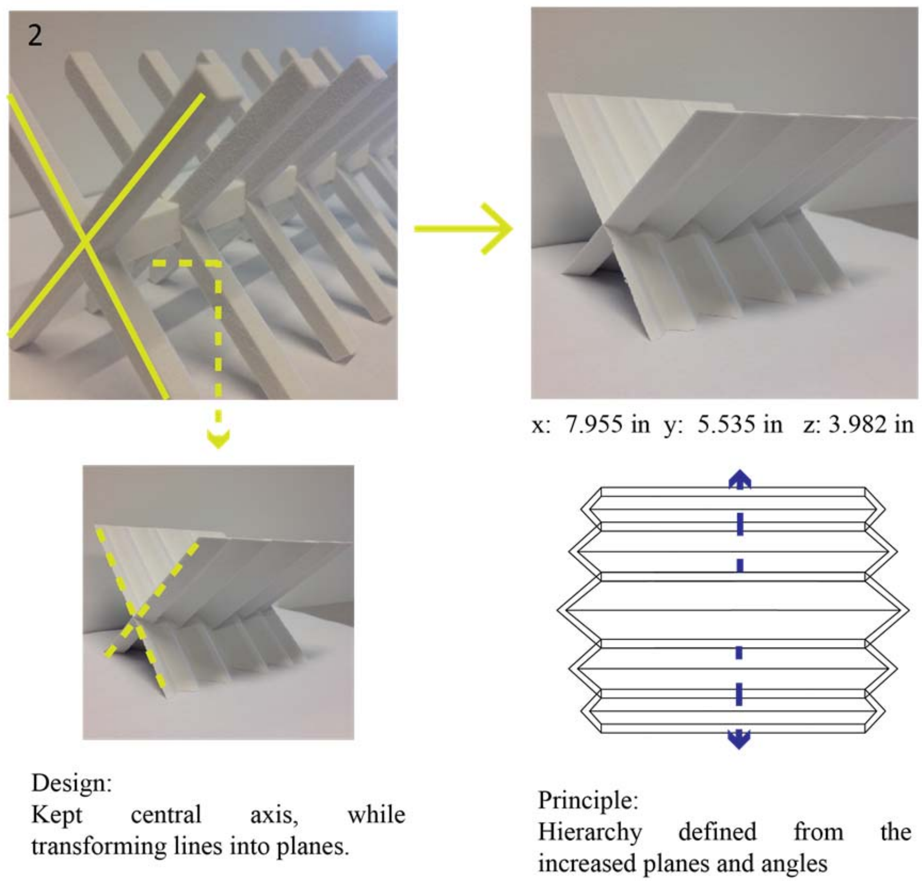


Figure 17. Product 7 Design Process

Pushing the design process forward, Product 7 continued to explore the fundamental design of Product 2. After analyzing the successes and failures of both the previous iteration and Product 2, I interpreted the design problem, and focused on form, function, and hierarchy in the redesign. In the design of Product 7, I reconstructed the repeated base pattern of Product 2 into planes using the Rhino commands Line, Surface, Loft, Mirror and Join. The product's design expressed hierarchy, as the width and depth of the planes increased from the outside to the center. It was hoped that this design realization would lead to a successful new solution to the design problem; and I would, of course, investigate and test the vessel after its 3D printing. The 3D print appeared to point to success of the design principle hierarchy, but further exploration of its form was needed in order to validate the product's success as a new design. This vessel model was able to hold a variety of fruit in various sizes, but the design did not respond specifically to this function. The planes should respond and securely fit the objects the vessel intends to hold. The scale and proportion of the planes were functional, but not evidently purposeful. I was able to generate these results through the effective 3DP printing of the vessel. The planes were seamlessly joined requiring no additional assembly. One affirmation regarding this product was the successful use of 3DP both as a means to ideate and as a fabrication method. Analysis through 3DP had enabled me to further develop my design process, as I continued to explore additional ideas and inspiration through printed physical forms.

Product 8

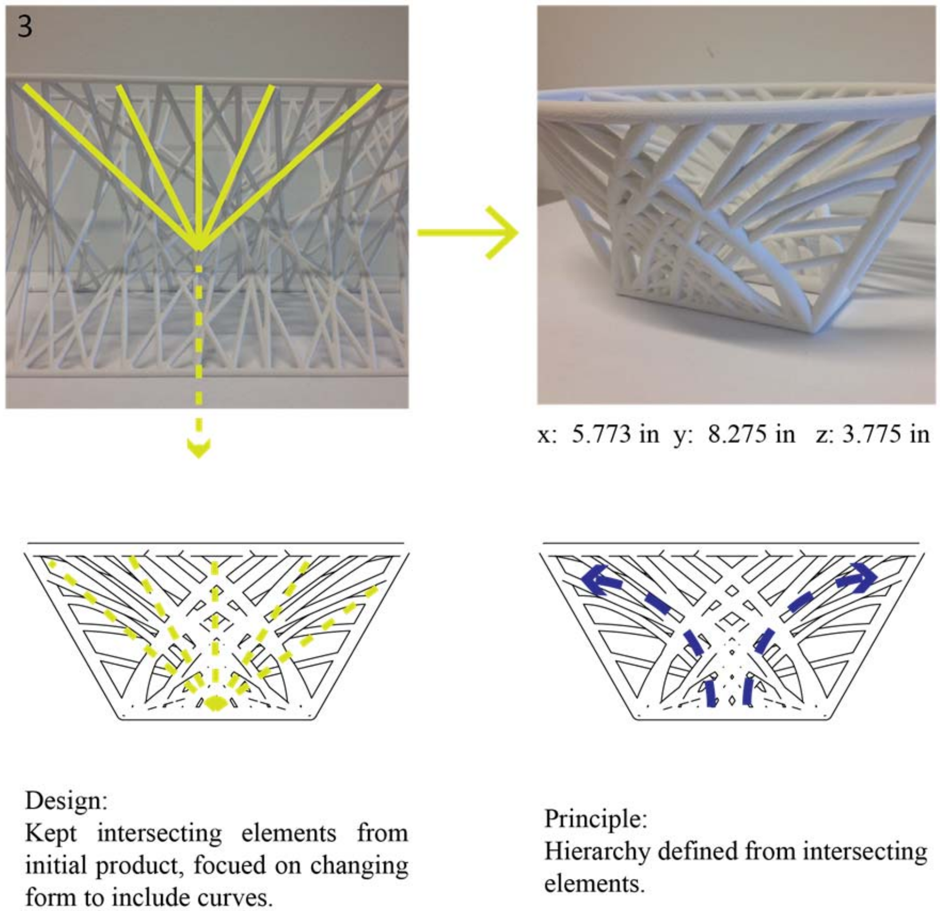


Figure 18. Product 8 Design Process

In the continued iteration of Product 8, I focused on the successes and failures of Product 3, while attempting to incorporate the principle of hierarchy. Structurally, Product 3 was not as viable, but it did illustrate the capabilities of 3DP as a fabrication method. Keeping these lessons in mind, I began the design process of Product 8 by focusing on hierarchy in the new design. I started with digitally manipulating the form and shaped it to curve by using the Rhino commands Line, Arc, Curve, Pipe, and Mirror.

I expected the product to create a better receptacle accommodating the general curved shape of fruit. The intersecting elements curved to produce the new form of the vessel and created a central focus through the enlarged diameter of each subsequent curve and the increased number of intersections in the middle of the product. The use of 3DP in my design process allowed me to test the product. I was able to determine that further experimentation with scale and proportion would make this product more appropriate. This particular design appeared to respond to and resolve the initial design problem, as the remodeled product form contoured to fit one larger piece of fruit and two smaller ones. The process was moving in the right direction. However, the issues were not fully resolved, as the capacity of the vessel was still limited and there was an awkward spacing between the base of the vessel and the bottom of the fruit. Fabricating this iteration using 3DP was a fast and effective way to replicate my latest design.

Product 9

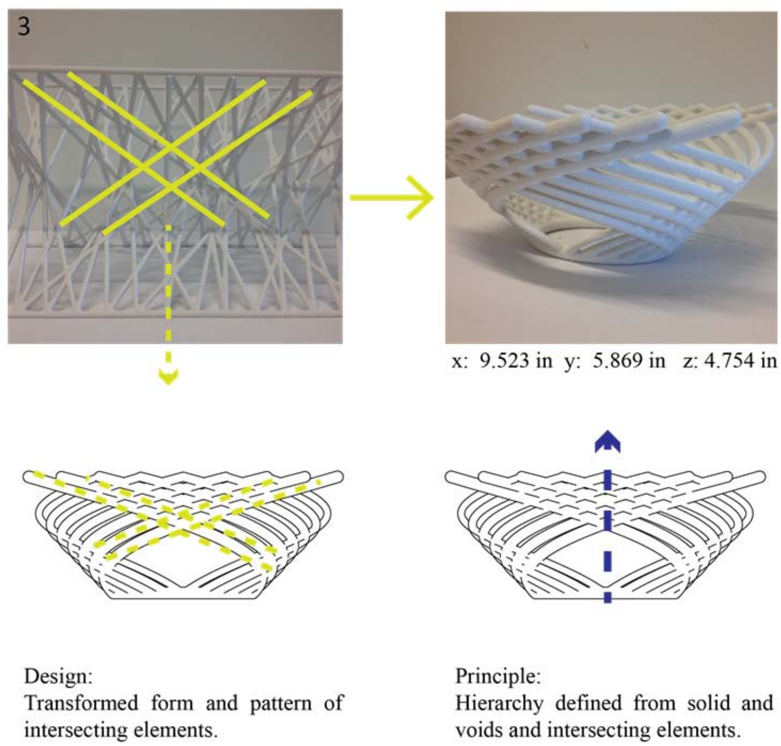


Figure 19. Product 9 Design Process

Continuing with the design process, Product 9 focused on restructuring the design of Product 3. In this iteration, I hoped to push the designs and concept of both Product 3 and the previous iteration further by addressing the defined problem through modifying the overall shape and form. To begin the exercise, I identified the known design flaws with both products and began to visualize design solutions digitally using Rhino commands Ellipse, Paneling Points on Surface, Curve through Points, and Pipe. In order to address their functionality, I continued with exploring a contoured form to fit the objects the vessel would hold. I also tried creating a more defined pattern with the design elements that would reflect the principle of hierarchy. After employing 3DP in the design of the product, I recognized both successes and failures in the design and form. The scale of the vessel was not appropriate, and I determined that either the overall size needed to increase or the form and/or elements could be altered to increase the capacity of the vessel. The principle of hierarchy was illustrated visibly in the model through the intersecting and non-intersecting line elements. The use of 3DP as a fabrication method was also encouraging, as Product 9 was structurally sound, and the complex geometry required no additional assembly. In the iteration of Product 9 3DP empowered me to envision this design possibility in its physical form and to make design decisions in my design process accordingly.

Product 10

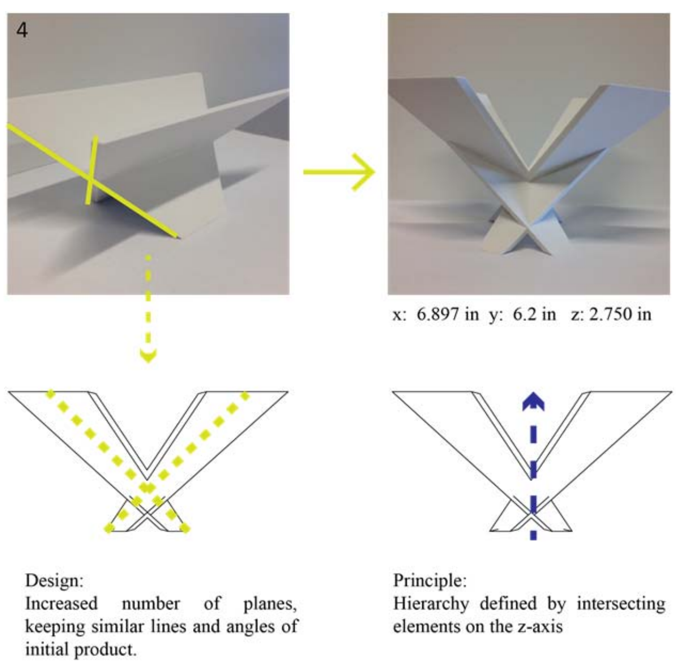


Figure 20. Product 10 Design Process

For this product, I decided to start with Product 4 and follow its modification relying on the principle of hierarchy. I was able to do that through the point of intersection of the planes. To begin the design process of this modification, I rethought the design issues from Product 4 as being basically problems with scale and proportion that affected the viability of its function. I started to test solutions digitally using Rhino commands Line, Surface, Loft, and Mirror through which I multiplied and manipulated the planes. I then 3D printed one possibility to evaluate and analyze physically. After testing the printed object with various fruits, I concluded that the scale and proportion of the object were appropriate for the function. The functionality of the model was assured since the geometric angles of the planes purposefully contained the fruit when tested. I decided that I would like to experiment with contouring the shape of the planes to see if it were even more successful. One of the primary benefits of using 3DP in the design process of item 10 was the ability to continue to conceive and test ideas quickly and easily, and I would utilize that advantage through all subsequent iterations.

Product 11

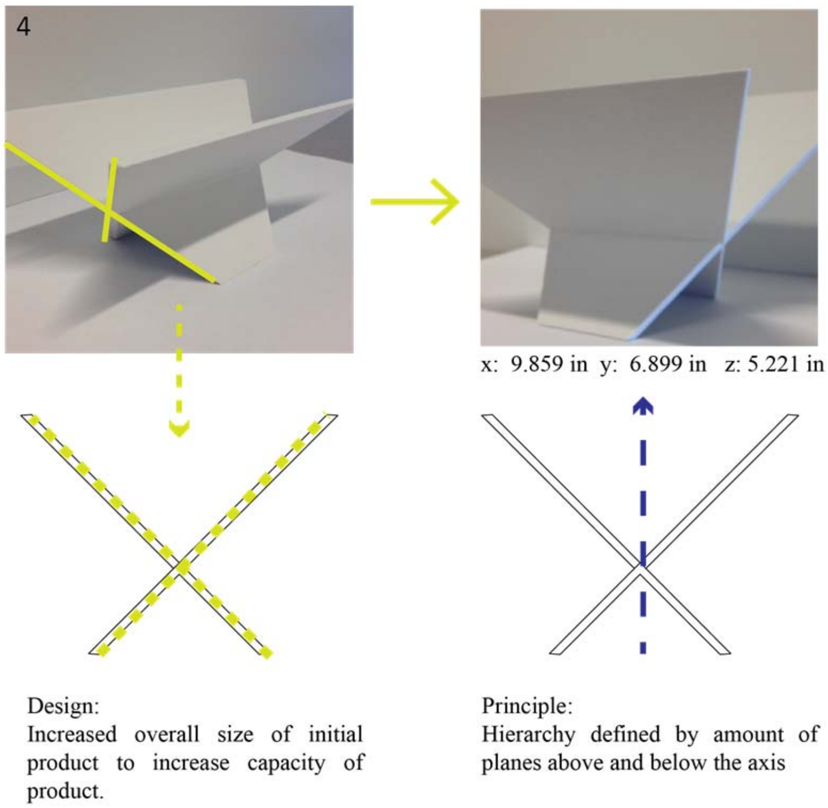


Figure 21. Product 11 Design Process

In the iteration of Product 11, I explored changing the scale and proportion of Product 4. There were some positive aspects of Product 4, in terms of form, but its small size was its greatest obstacle to being a useful container for various fruit. The redesign of this product focused on increasing the overall size of the previous product, while keeping the same form. As I also wanted to depict the principle of hierarchy, I could not just scale the original product digitally. I had to redesign the product according to the principle of hierarchy by locating the axis so that it changed its intersection with the planes from being centered on the planes to being lowered, making more of each plane visible above the axis. I used Rhino commands Line, Surface, Loft, and Mirror to do this. This design change not only effectively reflected the principle of hierarchy, but also helped to solve the original design problem, as this increased the overall capacity of the vessel. After using 3DP with the design, I was able to test the functional characteristics of the product. Although the product addressed some of the original design issues, there were still lingering concerns. The simple design, although aesthetically interesting, did not take advantage of utilizing 3DP as a fabrication method. If one does not utilize 3DP to the fullest, the cost of the process may not justify the results. Economically, the product could have just as well been prototyped using other, less expensive materials. I determined that even though I was able to use 3DP to test the physical object, in this particular case, because of the model's simplicity, I would have financially come out ahead by producing this prototype using alternate means.

Product 12

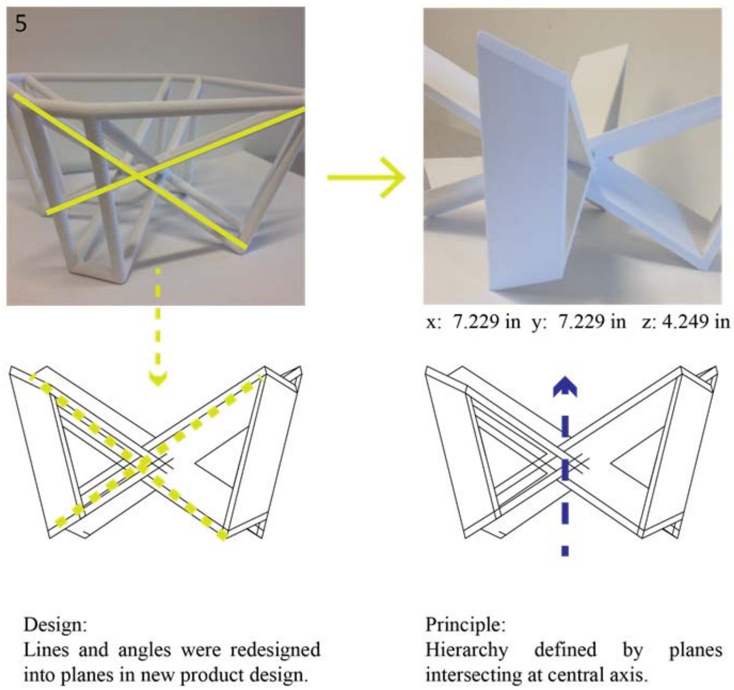


Figure 22. Product 12 Design Process

The next iteration continued the exploration of Product 5, but based on the principle of hierarchy. After identifying the design issues revealed in testing Product 5, I hypothesized on defining a solution. An obvious issue with Product 5 was the overall form, whose material and void elements limited its function as a container of various sized fruits. I considered transforming the lines of the original product into angled planes, intending therefore to increase the viability of the product. I used Rhino commands Line, Surface, Loft, and Mirror to model the new product. After taking the model through 3DP, it was evident that despite the fact that the surface area had increased, the spacing between the planes made the product even less functional.

Hierarchy had been alluded to by the design elements above and below the central axis, but the principle was not as definitively illustrated as in some of the other products. A particularly useful feature of utilizing 3DP as a manufacturing method was that the printing of interlocking joints required no additional assembly, as would probably be the case in other methods. Despite the lack of viability with this product, 3DP still provided an excellent instrument for testing and discovering design flaws, and determining ways to correct them.

Product 13

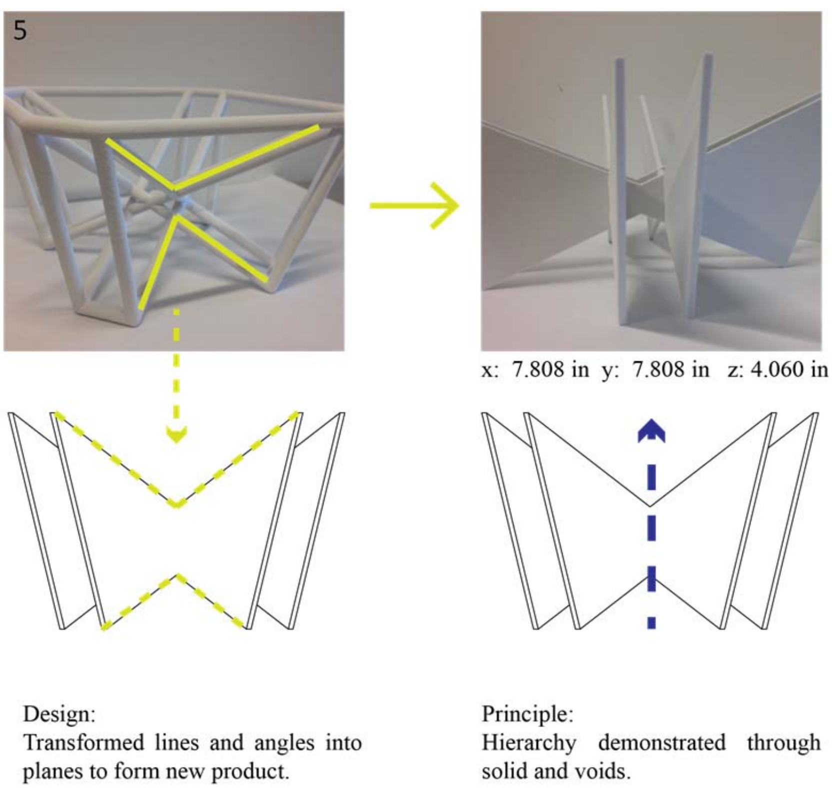


Figure 23. Product 13 Design Process

Product 13 also investigated the redesign of Product 5, and was the last product illustrating the principle of hierarchy. In this iteration, I aimed to increase the capacity of the vessel, while maintaining the use of solid and voids in the design. To start my design process, I digitally manipulated the design using Rhino commands Line, Surface, Extrude Surface, and Rotate, keeping the overall lines and angles from Product 5, but transforming them into planes that intersected in the center. I intended to illustrate Hierarchy in this model through manipulating the solids and voids of the container design. After evaluating the 3D printing of this design, it was clear that I still had not solved the problem of Product 12, even though I decreased the spacing between each element. The design was not as useful functionally, and further development was needed for this product to be more favorable. Nonetheless, through 3DP, I was able to test the spacing to measure its adequacy and gain insights as to how to redesign the product in future iterations.

Conclusion: Hierarchy

Overall, for this stage of the iterative design project, the more successful designs illustrating Hierarchy were Products 7, 8, and 9, while Products 7, 9, and 10 were the most viable functionally as vessels for holding fruit. In terms of analyzing the role of 3DP as a final fabrication method, Products 10-13 were not as suitable due to their lack of complexity and hence, unwarranted costs, while Product 6 had structural failure in its leg, as revealed through the 3D printed physical model. However, by utilizing 3DP, I was able to analyze each product physically, improve upon its weaknesses in design and function, and realize both the limitations and capabilities of 3DP as a fabrication method.

Rhythm and Repetition

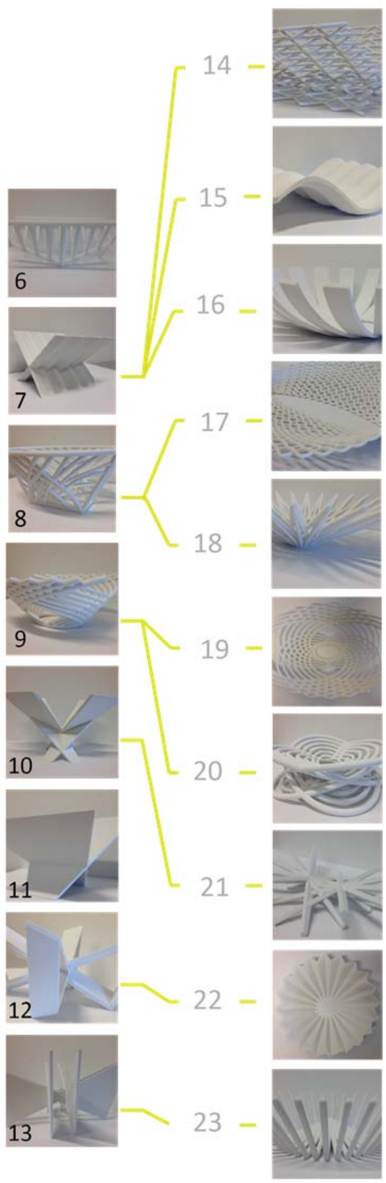


Figure 24. Product Design Iterations based on Rhythm and Repetition

The next ordering principles of design utilized in this iterative design project are Rhythm and Repetition. According to Ching (1996), rhythm and repetition refer to the use of recurring patterns and their resultant rhythms in order to organize a series of like forms and spaces. In this stage of the design process of the project, ten product iterations were designed and 3D printed.

Product 14

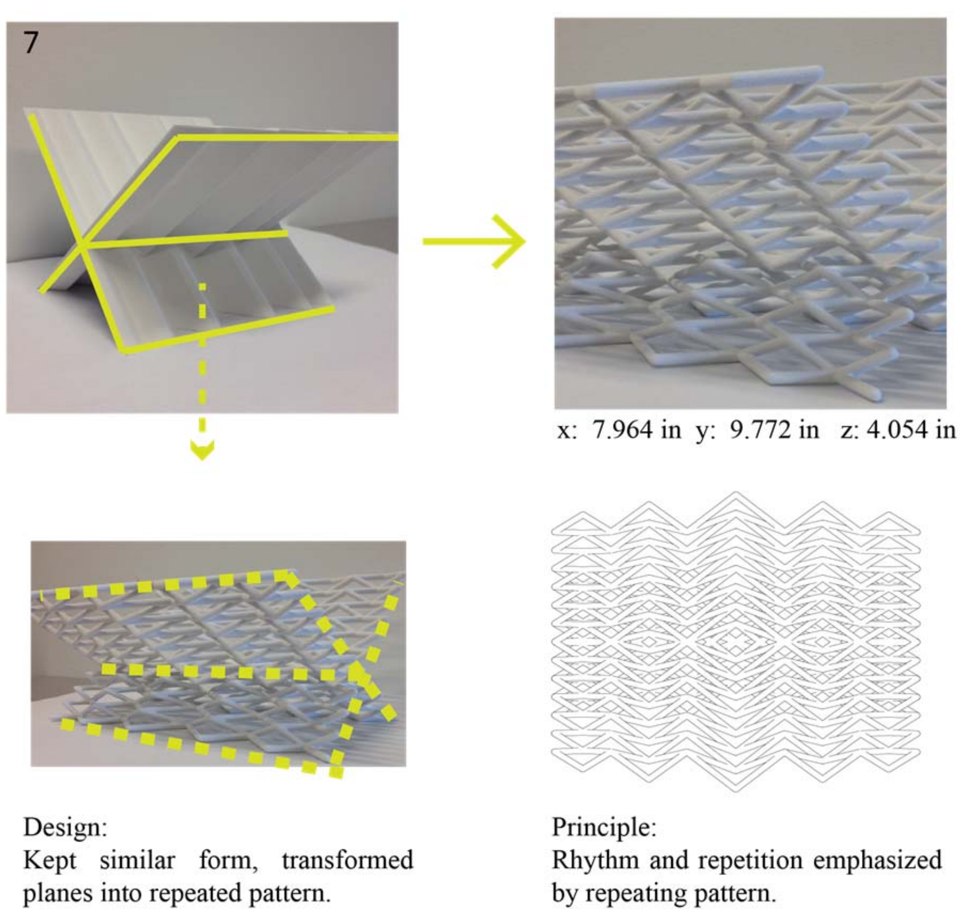
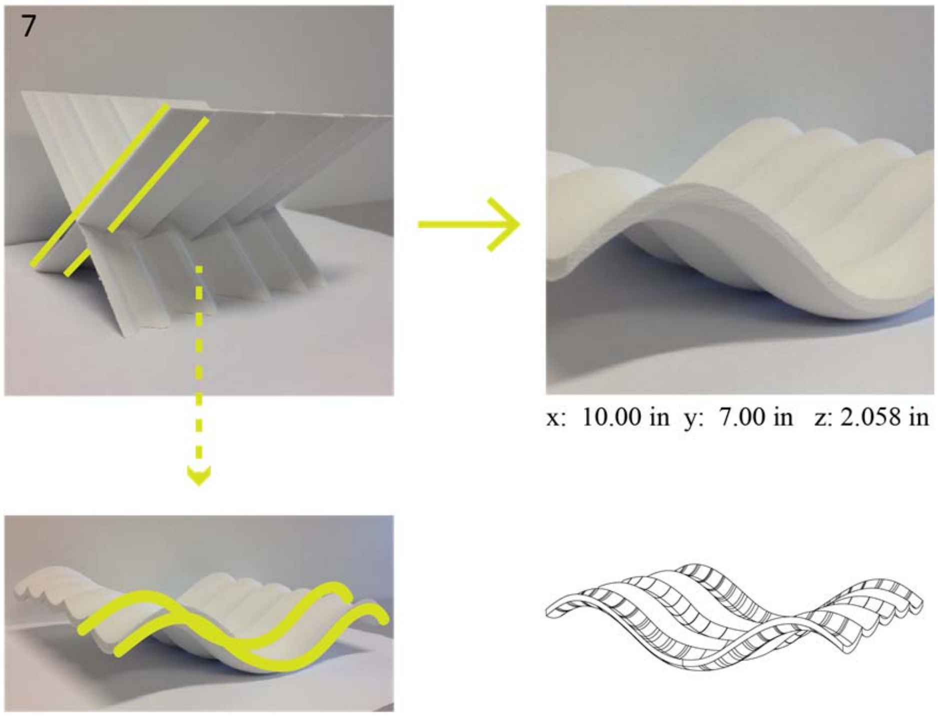


Figure 25. Product 14 Design Process

The first product developed at this stage in the design process was Product 14, which derived from Product 7 and explored the principles of rhythm and repetition. The design process started with analyzing how the new design principles could be utilized to improve the design and function of Product 7. I also wanted to further investigate 3DP as a manufacturing method, so I hoped to design complex forms that took advantage of using 3DP in the design process. As the shape and form of Product 7 was functionally satisfactory, I seized on manipulating the planes to better fit the potential contents of the vessel. Using Rhino commands Paneling Points through Surface, Line, Pipe, and Mirror, I digitally tried various patterns that varied in size to conform to the various sized fruit, but could also be repeated throughout the vessel—the guiding principle. Having arrived at an interesting design, I 3D printed the product to further evaluate the success of the function, principle, and overall viability of this modification. The product printed successfully and illustrated the many benefits of using 3DP in the design process. A positive feature was requiring no additional assembly of the complex form. Furthermore, the vessel was functional and emphasized the principles of rhythm and repetition effectively. But additional designs could be offered to further develop the product's individual elements as meaningful features that held fruit. I attempted to adjust the spacing and elements to test this, and although this iteration was more successful than the original product, I still was not satisfied. 3DP enabled me to visualize and realize the results of this latest digital design, incorporating the principles of rhythm and repetition, and suggested what changes might be made.

Product 15



Design:
Kept planes, transformed shape and form.

Principle:
Rhythm and repetition emphasized by repeated planes and lines.

Figure 26. Product 15 Design Process

Product 15 continued the investigation of the design of Product 7, but now through the design principles of rhythm and repetition. As Product 7 already illustrated repetition, the design of Product 15 aimed to alter the form by an increase of rhythm, function, and viability in search of a possibly new product. I began the process by digitally manipulating the form using Rhino commands Curve, Mirror, Loft, Surface, and Copy to transform the shape to create contours that would securely hold the various fruits. After using 3DP on the product, I tested the results to see the principles manifested in the form of the new model. The model seemed functional since the contoured elements and consequent new form allowed for various sizes and numbers of fruit to be held in the vessel. The distinctively shaped areas and the size of the contours increased from the outside toward the middle. Through 3DP, and after numerous iterations, I was able to analyze and evaluate the suitability of this product, which would inform the designer of possibilities for future iterations.

Product 16

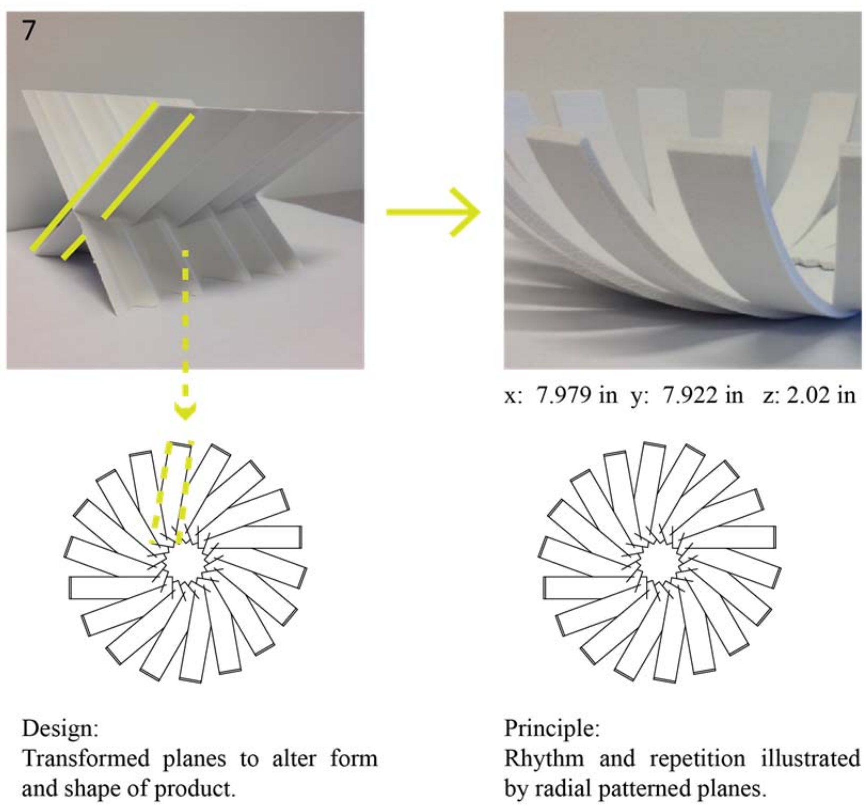
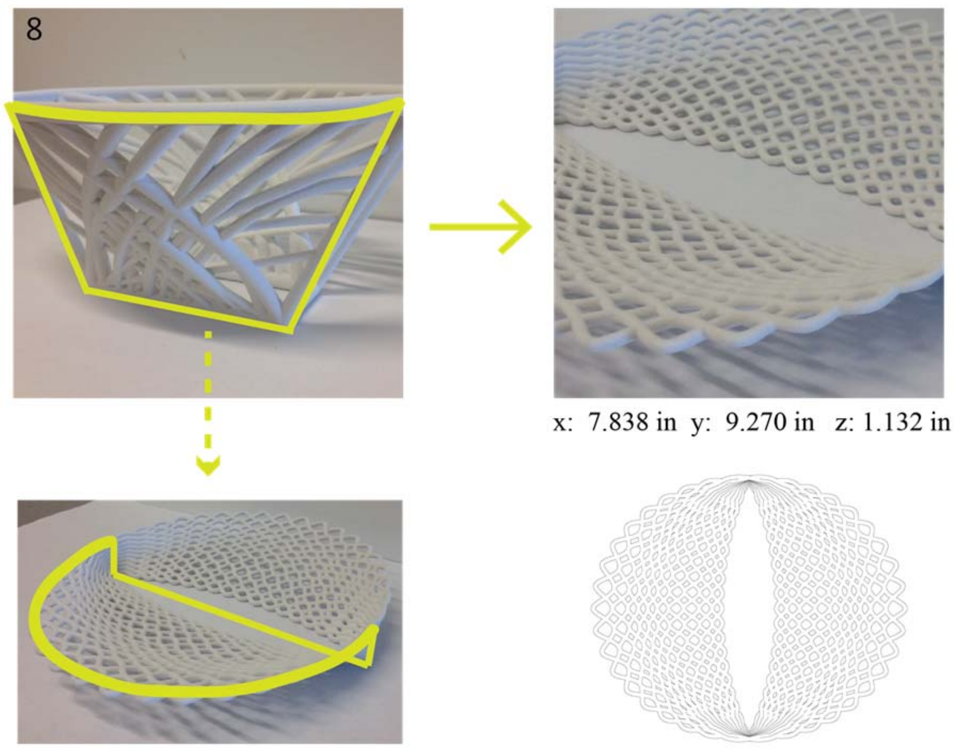


Figure 27. Product 16 Design Process

The next iteration continued the exploration of Product 7 through the principles of rhythm and repetition. The intent was to expand upon the existing elements and features of the initial product, but through a new, unexplored form. The design process for Product 16 started with contemplating the successes and failures of both Product 7 as well as the iteration prior to this one, Product 15. I analyzed how the change of form made the product more viable and decided to investigate a different form but with similar design elements. I digitally transformed the planes using Rhino commands Curve, Surface, Loft, Rotate, and Join to form a rhythmic radial pattern that illustrated the principles through the object's solids and voids. Through the use of 3DP, I was able to visualize the physical product and test the results. It was evident that the printed object illustrated the principles visibly Disappointingly, though functional as a container for a variety of fruit, the purposeful elements illustrated in Product 15 lacked in this design. Fabricating the vessel through 3DP succeeded, as each element seamlessly came together at the center of the object. Overall, using 3DP in the design process allowed me to test, visualize, and realize the successes and failures of this iteration, which in turn helped me address the next iterations and the overall design project.

Product 17



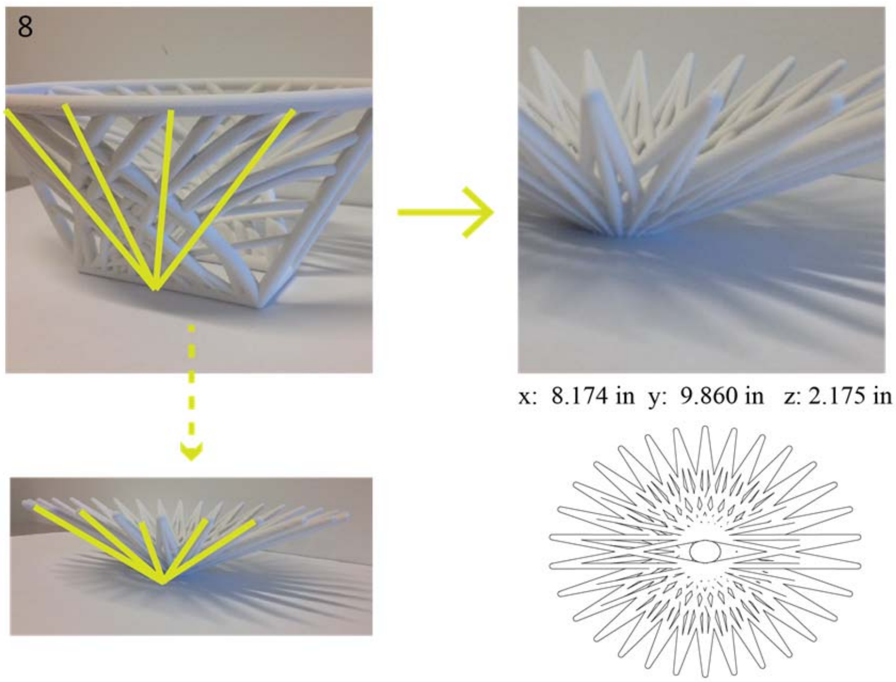
Design:
Kept similar form, but increased surface area and redesigned pattern.

Principle:
Rhythm and repetition illustrated through pattern that defines product

Figure 28. Product 17 Design Process

This iteration morphed the design of Product 8 through the additional principles of rhythm and repetition. In earlier steps of this design project for this vessel, I identified a design issue with Product 8 as its limited capacity to hold various fruit. I knew I wanted to expand the surface area of the product to eliminate this flaw, which could be done only through changing the overall form of the product. Digitally, I manipulated the form and the pattern to make the product more practical. I used the Rhino commands Paneling Points through Surface, Curve through points, Pipe, and Mirror to create the new product. I kept a similar shape, but changed the pattern and depth to see how that would affect the overall product. I also wanted to continue to explore the complexity of the original design, but with a more defined, purposeful pattern. Through 3DP, I was able to visually examine the result of this latest design. The complexity of the pattern not only demonstrated the efficiency and one of the prominent advantages of using 3DP, but also replicated the curves of the various fruit that could be placed in the receptacle.   Upon testing, I found the function of product quite satisfactory, as the design and expanded surface area allowed for a variety of sizes and numbers of objects to be placed in the vessel. Not having familiarity with and access to 3DP, I would not have been able explore this design option due to the complexity of the design and the time frame of the project. Fabricating this intricate final product by other manufacturing methods would be nearly impossible in a limited time frame.

Product 18



Design:
Explored new form, while extruding lines from central point to shape product.

Principle:
Rhythm and repetition illustrated radial pattern defined by elements.

Figure 29. Product 18 Design Process

Product 18 continued to iterate from Product 8 using the integration of the design principles rhythm and repetition. In the next step of the design process, I examined how I could continue to develop design solutions of the basic container. From Product 8, I hoped to alter the form and investigate how the individual elements could better define the product. Through digital experimentation, I created line patterns that connected to create the vessel using the Rhino commands Line, Point, Pipe, and Mirror. The new pattern was designed both to illustrate rhythm and repetition and to explore the fabrication capabilities of 3DP, while attempting to improve on the function and usefulness of the product. The product was 3D printed successfully, requiring no additional assembly, and the patterned elements seamlessly blended together at the center—criteria for a good print. With the physical print in hand, I tested the functional qualities of the new design as the surface area had been enlarged in hopes of increasing the overall capacity. Although the latest design could hold more objects, which was an improvement on the design of Product 8, this product was not as overt as Product 17 in defining its function. Nonetheless, through the use of 3DP, I was able to physically critique the new design and determine ways to improve future iterations.

Product 19

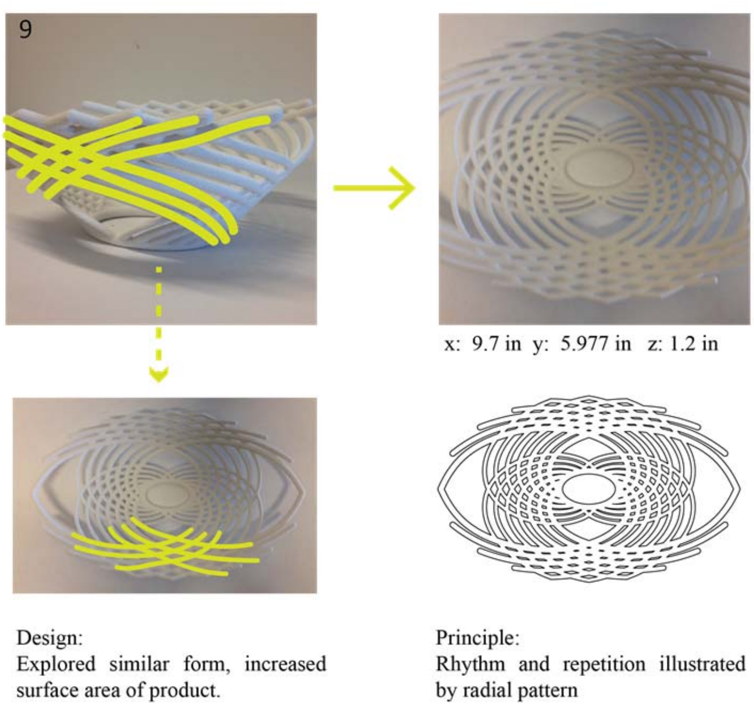


Figure 30. Product 19 Design Process

In this iteration, I again focused on evolving the design of an earlier product, Product 9, through rhythm and repetition. To begin the design process of this product model, I thought about how I could push the design forward from the previous iteration. I recognized the need to improve upon the scale of the previous product, so I digitally played with taking a similar design and changing its shape to increase the surface area of the vessel using Rhino commands Ellipse, Paneling Points on Surface, Curve through Points, and Pipe. Once more going through the procedures of 3DP, I was able to assess the functionality and overall viability of the design. The product obviously illustrated rhythm and repetition through its design elements as well as served more viably as a container for a wider variety of objects. This complex form utilized the many advantages of 3DP as a fabrication method, and was also one of the least expensive products to print. Overall, Product 19 could be considered as a potential design solution and even a viable new product.

Product 20

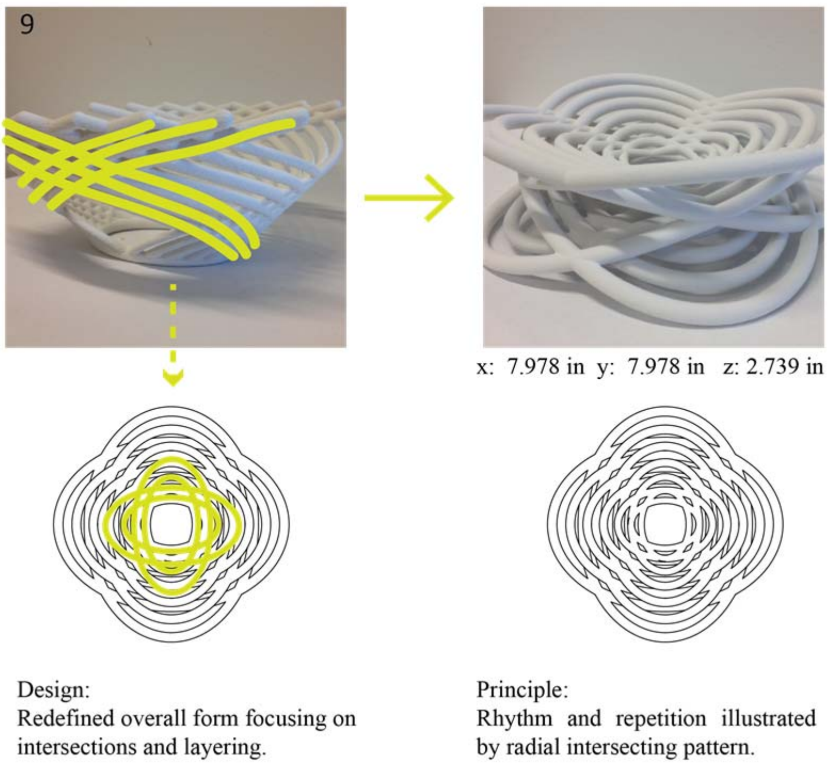


Figure 31. Product 20 Design Process

Product 20 resulted from the redesign of Product 9, illustrating rhythm and repetition. As I have now repeated this process numerous times, I have learned that the best way to begin the design process is by identifying exactly what I wanted to explore in this new design. I concluded that I wanted to examine a new form that would enhance the product's functionality as well as encourage the use of 3DP in fabrication. I aimed to redesign the vessel digitally by creating intersecting patterns that utilized the z-axis. I intended to express the principles through these intersections. I used the Rhino commands Ellipse, Offset, Pipe, Rotate 3D, and Mirror to create the new design. After applying 3DP to the iteration, I was able to test the object for functional realization as well as analyze the design and overall quality of the final product. The design indeed increased the capacity of the vessel, but in economic considerations, printing this product by the 3DP process was probably unjustifiably expensive. Rhythm and repetition were illustrated well, and this complex form properly utilized 3DP as a fabrication method, but the form still needed further evaluation in order to be a purposeful vessel to hold fruit. For this latest iteration, using 3DP in the design process had both positive and negative aspects. I was able to push the envelope in using 3DP and understanding its capabilities, but since this product was not as advantageous overall as some of the previous iterations, I ended up spending more money only to realize that there were some shortcomings in the design. As I have repeatedly noted, failure in research and experimentation is not an unmitigated disaster, but rather is one of the most effective instructors, especially in the experimental use of new technology, such as 3DP.

Product 21

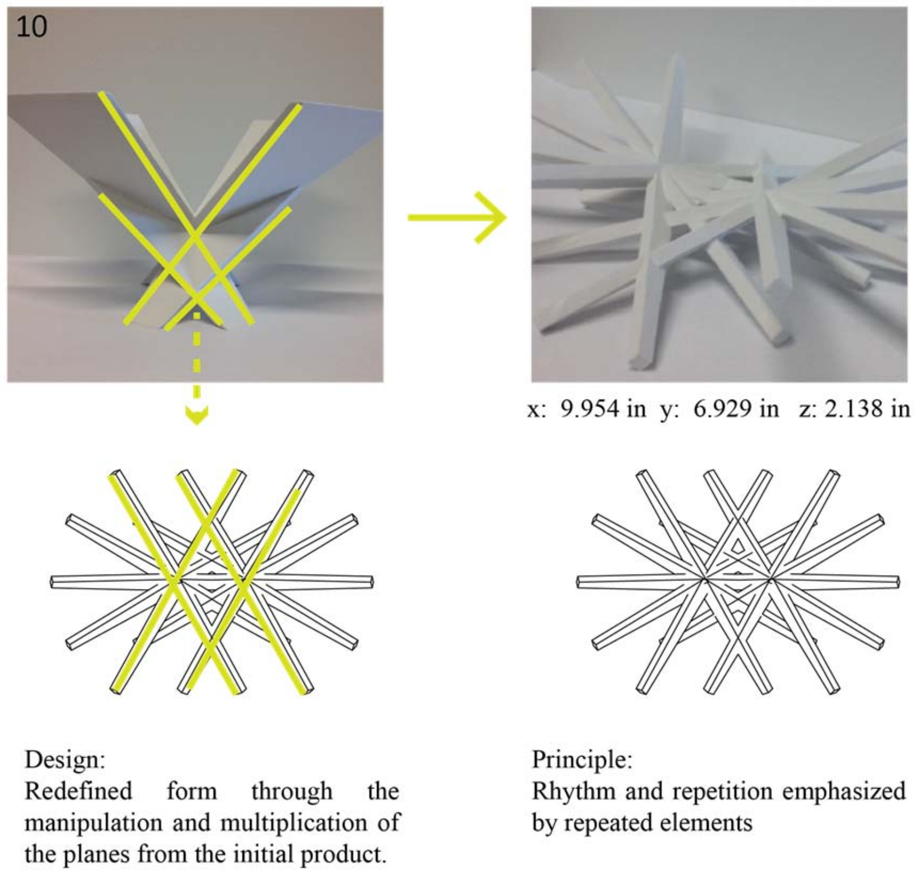


Figure 32. Product 21 Design Process

In the design of Product 21, I essentially redesigned Product 10, incorporating rhythm and repetition. I started to think about how to push this iteration forward, and as the functionality of the previous iteration was encouraging, I decided to explore how to increase the complexity of the design to make 3D printing an even more advantageous fabrication method. Using the Rhino commands Line, Surface, Extrude Surface, Rotate, and Mirror, I digitally tried transforming the planes into lines while focusing on how the intersection of the elements could affect the function. By increasing the number of elements I had hoped to limit the open spacing and create a more functional product. Through the use of 3DP, I was able to fabricate the revamped product and assess the viability of both the design and function. As the redesign focused on the intersecting elements, I used 3DP to test the spacing between each element. In the process I learned that the product was not as functional as I had expected in holding various sized objects. In this iteration, I felt that the function and viability of the product was not as satisfactory as the iteration it derived from, but 3DP technology nonetheless enabled me to discover this in a quick and effective way.

Product 22

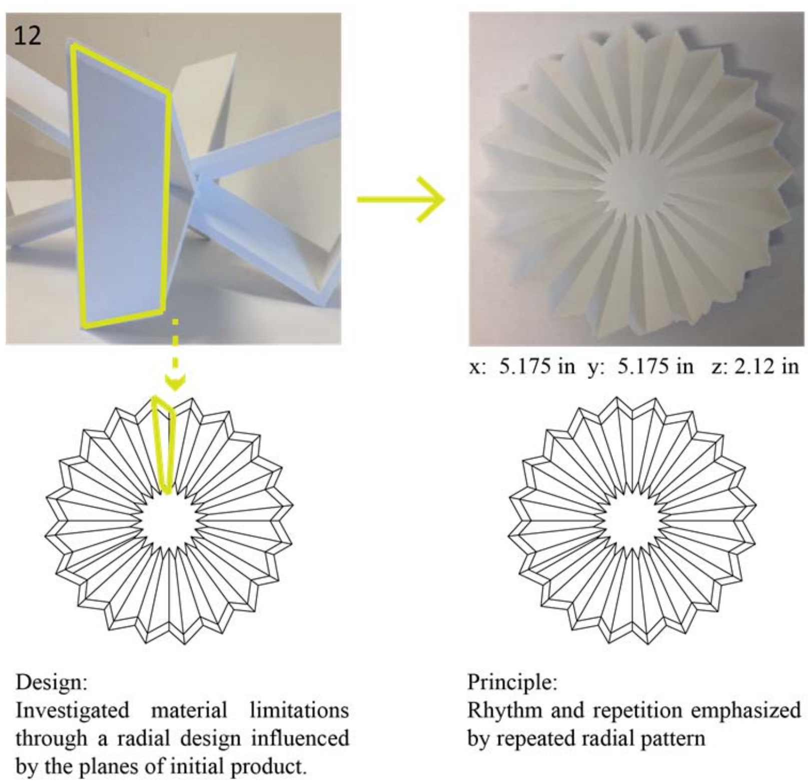


Figure 33. Product 22 Design Process

Product 22 aimed to further investigate the design of Product 12, while incorporating the principles of rhythm and repetition. In this product revision, I wanted to further understand the capabilities and restraints of the z-corp 3D printer, so I chose this iteration to see if I could push the limits on the wall thickness of the composition material. With this goal in mind, I presumed the functionality and overall viability of the product would be compromised. Digitally, I used the Rhino commands Line, Surface, Extrude Surface, and Rotate to take the lines from the previous design and created planes that radially rotated around the central point to try and illustrate rhythm and repetition. As the planes were completely connected, I made the wall thickness 1/16th of an inch, which is less than the recommended 1/8th of an inch, but I wanted to see how the material would respond. After completing the 3DP process, I discovered that although the structure was physically weak, the final product was intact and actually flexible, which was an unusual property of the gypsum powder. Although this resulting product was not viable by most of my criteria as it was not structurally strong and had scale issues, going through this experimental design process with 3DP was informative to my further understanding of the capabilities and restraints of 3DP as a fabrication process.

Product 23

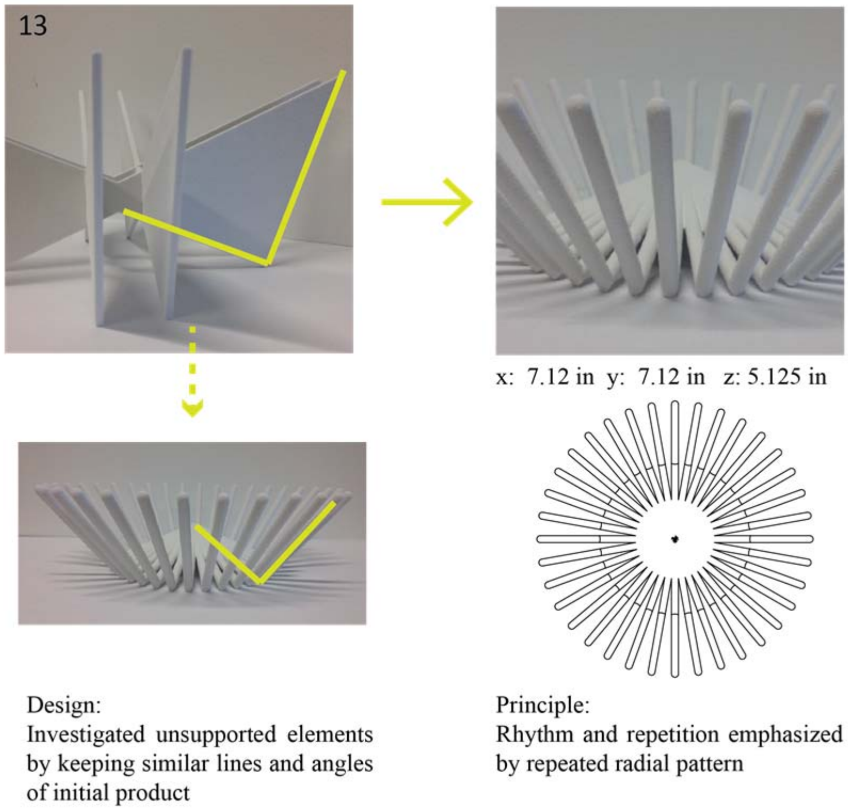


Figure 34. Product 23 Design Process

This iteration evolved from Product 13 and aimed to incorporate rhythm and repetition as a primary element of the design. To begin this design revision, I decided that I wanted to continue to experiment with the limits of 3DP and the gypsum powder material before I got to the Transformation stage of the iterative design project. Since Product 22 investigated wall thickness, I wanted to use Product 23 to discover the structural strength of unsupported elements. In the design, I used the lines from Product 13 and rotated them around a central point to create a radial rhythm. The elements only connected at the central point, but extended up without additional support. In order to create this new product, I used the Rhino commands Line, Rotate 3D, Pipe, and Rotate. Through the use of 3DP, I was able to realize the design in physical form. As this product was designed to push the capabilities of 3DP, some of the elements of the design broke during the cleaning process, but encouragingly most of them remained intact. Although this product is not as viable structurally or functionally, the iteration allowed me to learn more and experience further the advantages and drawbacks of 3DP and the gypsum powder material. These experiments contributed to a critical understanding of the use of 3DP in the design process.

Conclusion: Rhythm and Repetition

Overall, Products 15, 17, and 19 were superior functionally as vessels for holding fruit. As illustrations of rhythm and repetition in the design of each product, Products 14, 15, 17, and 19 served best. 3DP was utilized most effectively in Products 14, 17, 19, and 20 because their complex designs would have been difficult to fabricate using alternative methods. Not only the advantage of printing complex 3D items, but other leading advantages of 3DP as a fabrication method were also incorporated, such as the fact that no assembly was required after printing. In terms of efficiency, each product was redesigned and fabricated in less than 24 hours, a time frame few other production methods could hope to match. This rapid prototyping allows one to analyze and evaluate each physical product quickly and be better informed to modify the next iteration based on the successes and failures of the previous efforts. However, the cost still remains a consideration throughout my design process. The products with more material volume are more expensive, and learning how to analyze the cost of printing to the benefit of having a 3D print to evaluate has been a critical outcome of this project.

Transformation

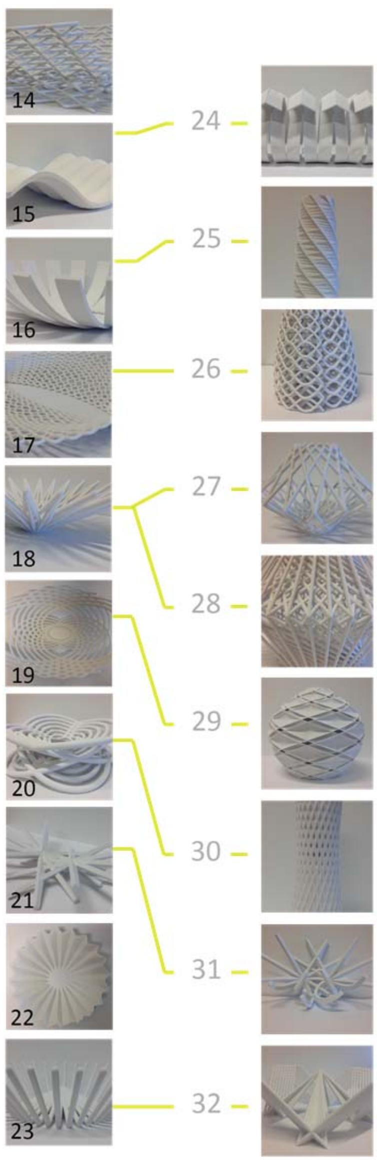


Figure 35. Product Design Iterations based on Transformation

The last stage of the iterative design project explored Transformation as the final ordering principle of design as an element of change. According to Ching (1996), Transformation is the notion that a concept can be clarified, strengthened, and/or built upon through a series of manipulations. In regards to Transformation, this last factor was applied to the project as a means to alter the product's function—but still incorporating the results from the previous design iterations. In this stage, nine products emerged from the application of Transformation.

Product 24

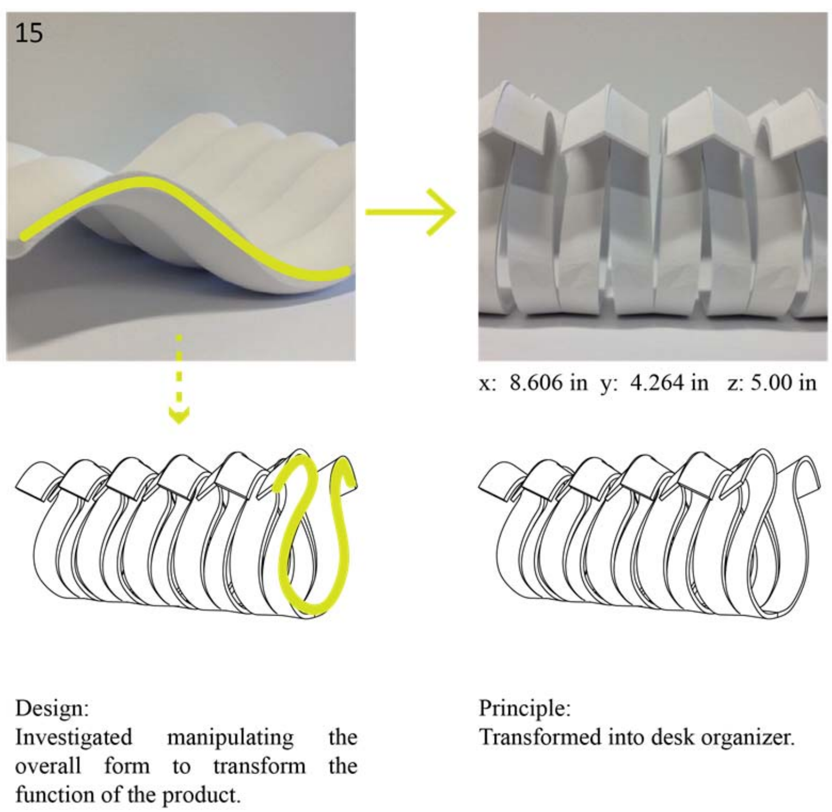
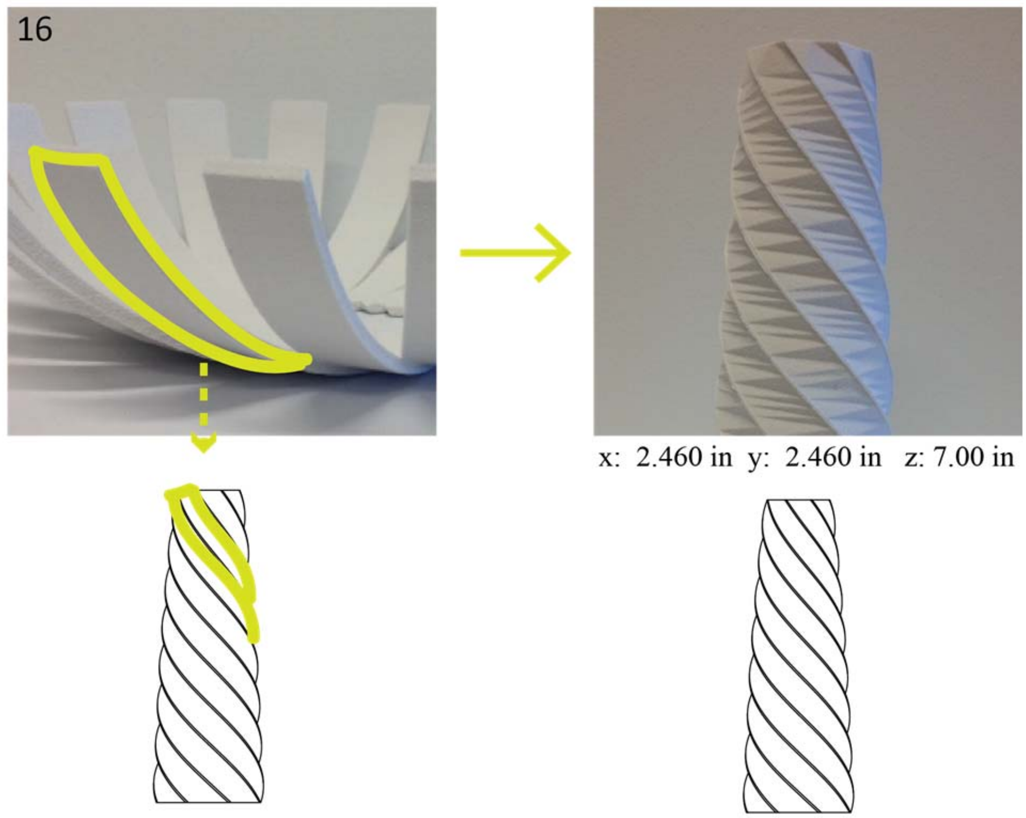


Figure 36. Product 24 Design Process

Product 24 evolved from Product 15 based on the ordering principle of design Transformation. At this stage of the project, after numerous successes and failures, I hoped to have a better understanding of 3DP as a fabrication process and as an iterative design tool in the design process. I began the design process of this iteration by trying to determine how to transform the product from the previous iteration in hopes of altering the function of the new product. In this attempt I wanted to manipulate the form of Product 15 to become a new kind of container. Through digital transformation, I altered the form and planes to create a desk organizer by using the Rhino commands Line, Surface, Loft, Mirror, Copy and Join. Through the use of 3DP, I was able to test the new function and the overall suitability of the design. The planes curved with some spacing in between to allow letters or papers to be placed in the product two different ways, either compartmentalized or along the center. The openings proved functional and conformed to the size of the objects the desk organizer was supposed to hold. 3DP demonstrated its advantage as a fabrication method by not requiring additional assembly to build this new product. Overall, this adaptation of the original concept was functionally adequate, but not as appealing aesthetically. But using 3DP allowed me to analyze this possibility as a new design.

Product 25



Design:
Investigated twisting the planes of the original product to transform the funciton.

Principle:
Transformed into vase.

Figure 37. Product 25 Design Process

In the design of Product 25, I transformed Product 16. I started this design process by contemplating how I could strengthen the function of the product from the previous iteration through the principle of transformation. I digitally manipulated the planes of the previous iteration by twisting them as they came together, resulting in a new style of functioning vase. To create the 3D model of this product, I used Paneling Points through Surface, Line, Circle, Offset, Loft, Join, and Rotate. Through 3DP I was able to conceptually realize the new physical product, and after printing, to assess its new form and function. After testing the new function with its ability to hold up vertically, I was able to claim at least limited success; however, due to the nature of the composition material, I was unable to test the vase's ability to hold water. I hope to continue to experiment with various materials beyond this prototype to test this characteristic of the vase design. 3DP served once more as an effective fabrication method, since the details of the morphed final design would have been difficult to produce using other fabrication methods. The shape of the vase lacked creativity when compared to other vessels for holding flowers, but the intricacies of the created form, the numerous and complex iterations that enabled me to arrive at it, and the 3DP fabrication method make this design a satisfying and functional product.

Product 26

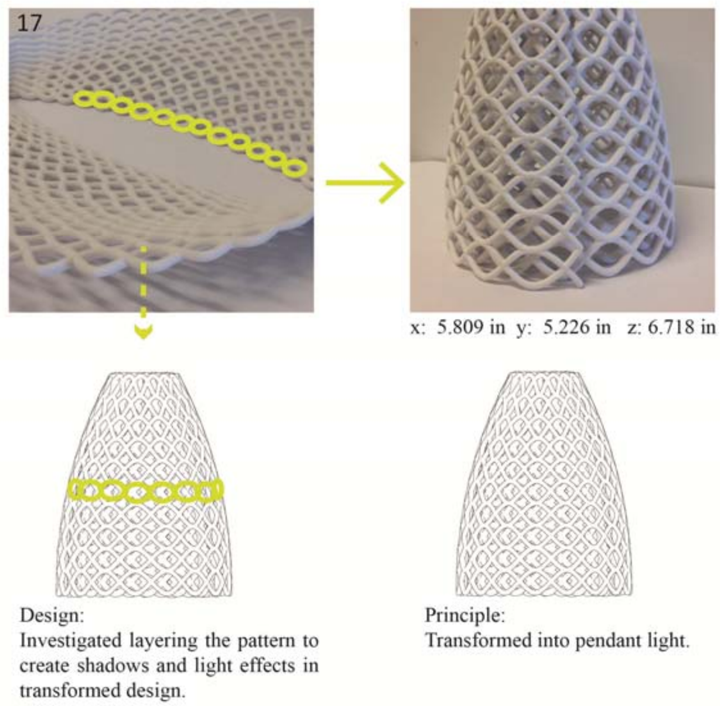


Figure 38. Product 26 Design Process

Product 26 iterated from Product 17 through the principle of transformation. To begin this design transformation, I rethought the previous iteration's strengths and weaknesses as well as the product's design, which would inevitably partly dictate how to transform Product 17. I noticed how the pattern in Product 17 cast interesting shadows, which encouraged me to digitally investigate how to transform the product into a light that focused on creating unique light and shadow effects. In the new product, I also wanted to utilize the advantages of using 3DP as a fabrication method. As a result I designed a complex pendant light that used a similar pattern from the previous iteration using the commands Ellipse, Loft, Paneling Points through Surface, Curve through

Points, and Pipe. The pattern wrapped around in three layers to form the pendant, and each line of the pattern decreased in diameter from the outside to the inside. Through the use of 3DP, I was able to design and fabricate this new product, a complex transformation of an earlier model. As before, I tested the results to analyze the qualities of the new function and overall design. As a pendant light, the product proved stylistic and imaginative. The layering of the pattern hid the light source, but also created appealing light and shadow effects. Without 3DP, I would not have been able to conceptualize the realization of this innovative product, nor would I have been able to recognize the potential for a new function, since the transformation could have occurred only through the iterative design process using 3DP.

Product 27

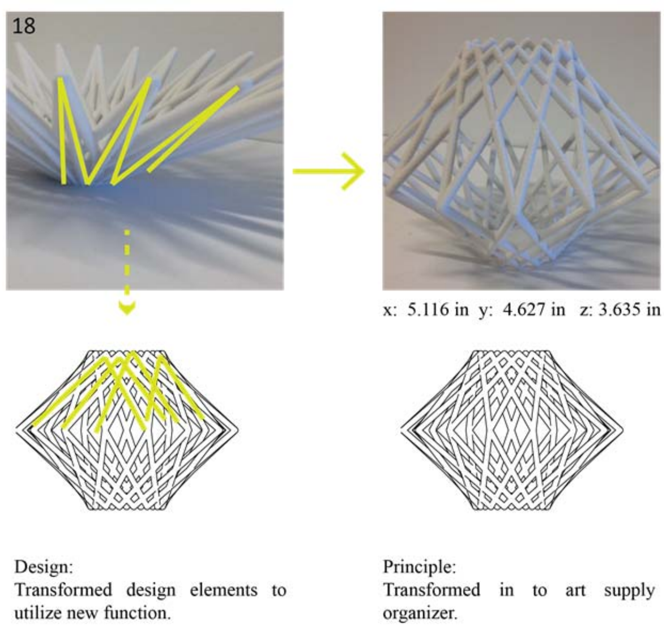


Figure 39. Product 27 Design Process

Product 18 directed the design of Product 27 through the principle of transformation. The design process of this product began by reviewing the iterative design process that led to the design of Product 18. Through that process, I discovered that each design entailed connecting patterned elements that seemed to aim at some define purpose in the product. Continuing with that design property, I digitally experimented with transforming the product and its elements into an art supply organizer with specific spaces for each tool. I used the Rhino commands Line, Pipe, and Mirror to create the new product. After utilizing 3DP for the newly transformed product, I assessed the new function and design by testing the specific spaces with various art supplies. I determined that although the design was able to accommodate a variety of supplies, the design of the product did not inform the user of the specific use of each space. This could be viewed both positively and negatively, as the product could be seen as more versatile, or it could be viewed as more prescriptive. Regardless, I concluded that further iterations and more design development would have to occur in order for this new product and its corresponding function to be fully viable.

Product 28

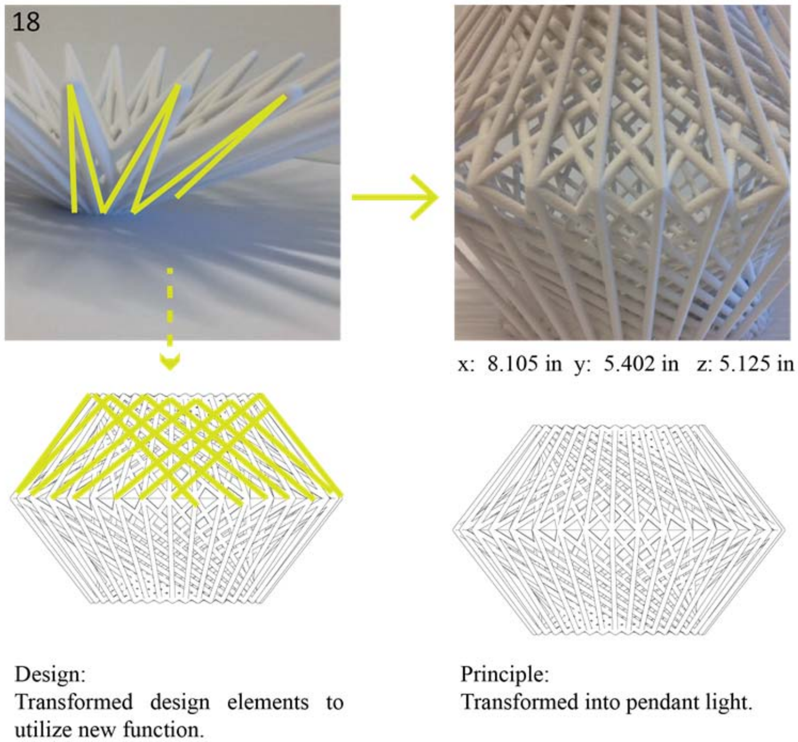


Figure 40. Product 28 Design Process

Product 28 also descended from the design of Product 18. I chose to transform another design from Product 18 because I wanted to further examine how I could incorporate the light and shadow effects that existed in Product 18. I used a similar design aesthetic as Product 27, but added more patterned elements to try and hide the light source when I transformed the product into a pendant light. One aspect that I wanted to continue to explore was the 3DP of unsupported elements, similar to what I did in design of Product 23. I used the Rhino commands Line, Pipe, and Mirror to create the new product. After undergoing the 3DP procedure, it was revealed that the unsupported exterior elements of the new light were very brittle and broke as I attempted to remove the product from the print bed. Due to the fragility of the product, I was not able to test the effectiveness of the new function. Further design development in regards to materials was needed in order to for the iteration to be credited a success as a transformed product and as a durable 3D printed object. Through the use of 3DP, I was able to assess the flaws with this product but remained optimistic that with some modifications this could result in a viable iteration.

Product 29

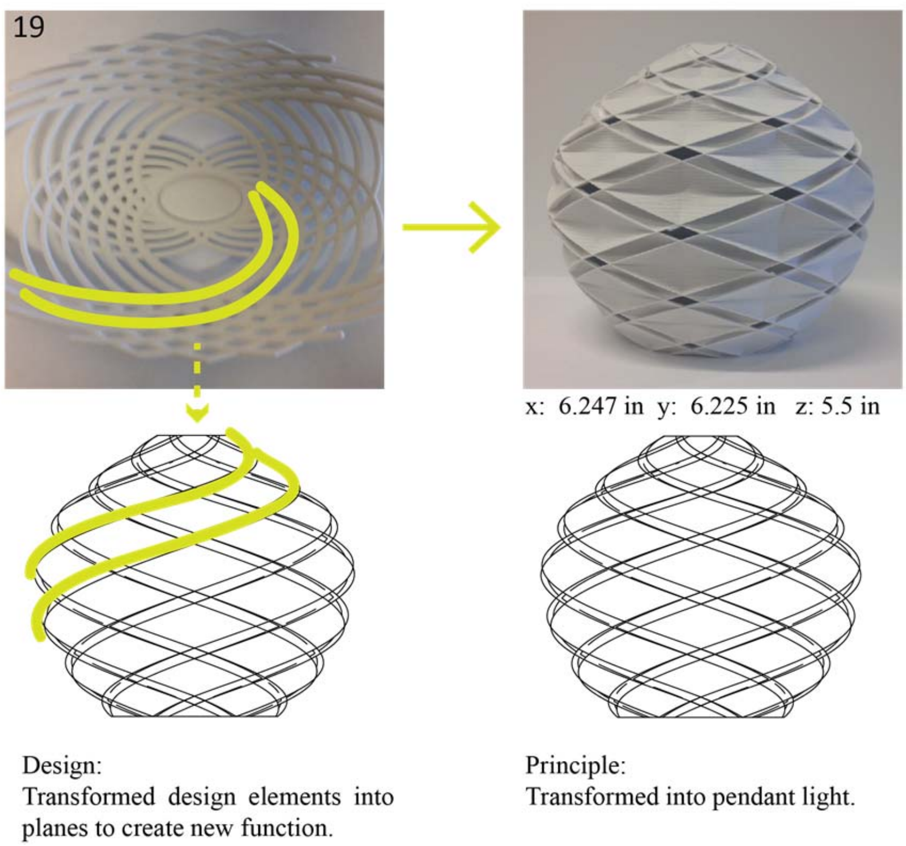


Figure 41. Product 29 Design Process

The design of Product 29 was inspired by Product 19 and materialized through the principle of transformation. After assessing Product 19, I recognized the intricate pattern that also created light and shadow effects. Having a physical product to analyze and hold close to light sources to investigate the various patterns was of tremendous benefit in using 3DP in my design process. Following similar lines as in developing Product 19, I digitally transformed the lines into planes, as I changed the function of the product to become a pendant light using the Rhino commands Ellipse, Loft, Paneling Points through Surface, Curve through points, Offset, Loft, Surface, Rotate, and Mirror. I was then able to 3D print the new model to evaluate its physical success. Through testing with an added light source, I was able to determine that the planes successfully covered the light source while emitting light through the small openings of the pattern and also through the thinner areas of the material. This product turned out to be one of the more successful products from this iterative design project, as its evolution was clearly exhibited through each advancing stage in the iteration. The new pendant light also utilized the advantage of 3DP as a fabrication method, since it required no additional assembly aside from adding a cord and a light source—which at this point in the technology, cannot be replicated. 3DP enabled me to realize this new design possibility.

Product 30

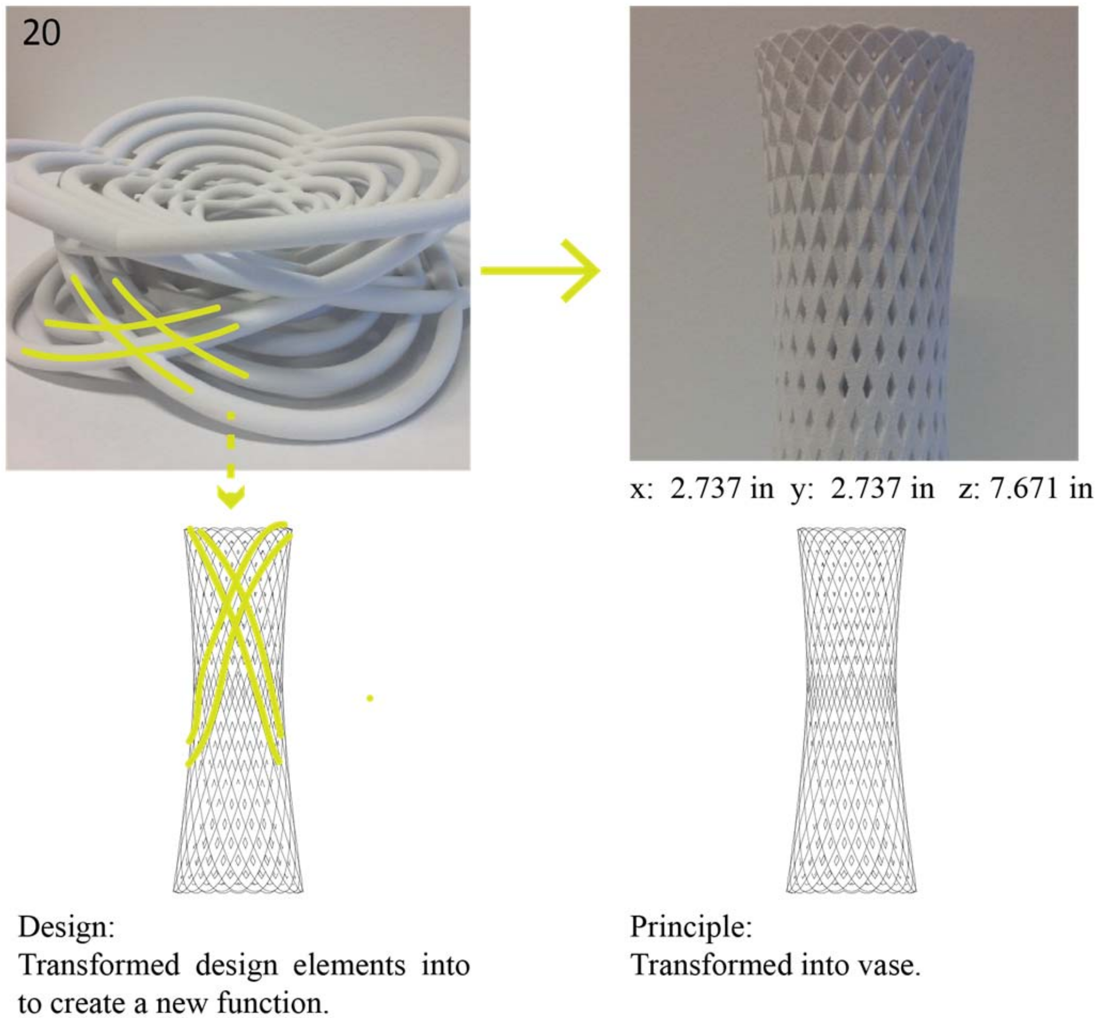


Figure 42. Product 30 Design Process

The design transformation that occurred in Product 30 was inspired by Product 20's design. Through analyzing the successes and failures of the previous design, I speculated on how I could manipulate the specific design elements and their use of intersections to create a new, viable product. I began by digitally manipulating the lines and intersections to change the shape, which resulted in the new form and function as a vase. I used the Rhino commands Ellipse, Offset, Loft, Extrude Surface, Rotate 3D, and Rotate to create the new product. The design incorporated a new pattern combining solid and voids of the previous iteration, in which the closed openings were at the bottom, so that water could be held in the vase. Through the application of 3DP, I was able to evaluate the features of the product's design and function. The product successfully held up objects vertically, but due to the prototyping nature of the gypsum powder, I was, as before, unable to test the product's ability to hold water. This is one disadvantage with testing products in certain, inappropriate materials, but if I were to continue exploring this product, I could 3D print this object in ceramic, which I could test for its ability to hold water. Familiarity with 3DP at this stage in the design process has allowed me to practice digital design according to intended functions and achieve considerable success in general design and production.

Product 31

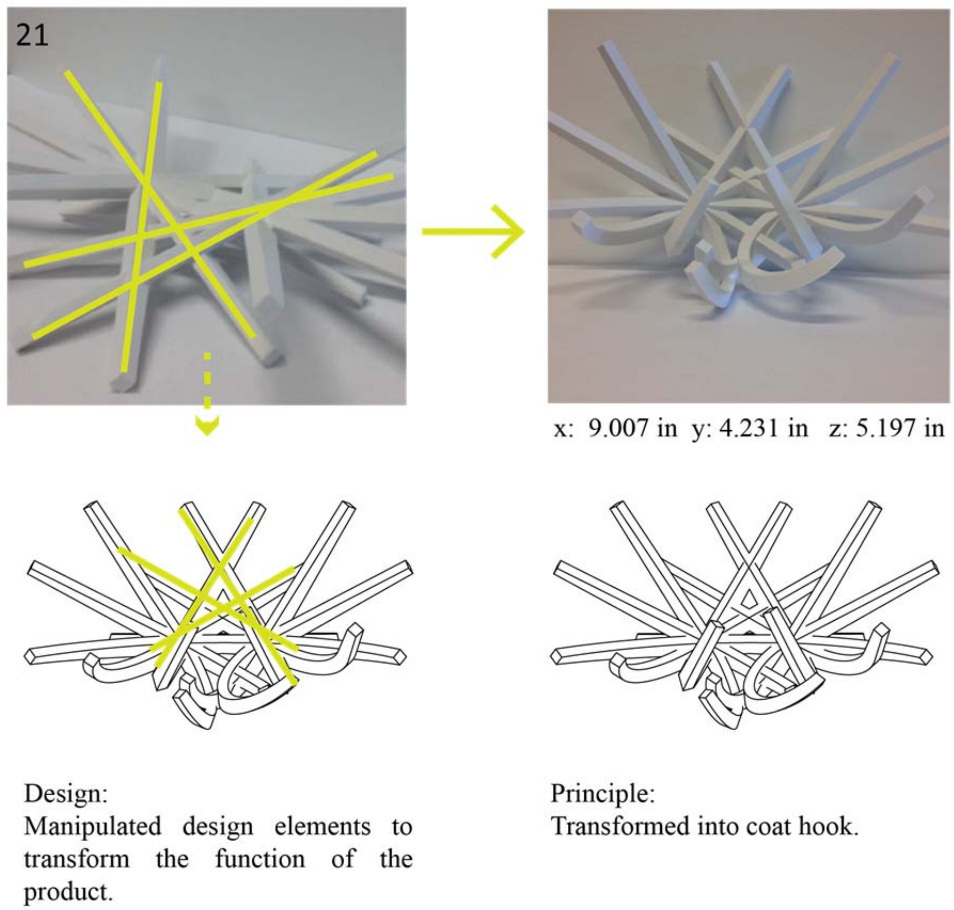


Figure 43. Product 31 Design Process

Product 31 was transformed from Product 21. The design process of this object started after I reevaluated the form and function of Product 21. As I realized the product's shortcomings, I hoped to correct these and continue the product's evolution toward finding a new function. I began by digitally redesigning the product and making the individual elements that were spaced too far apart to properly contain objects more purposefully as a design element of the product. I stretched the elements on one side and added a wall-hanging attachment on the back, as I transformed the vessel into a coat hook that could be hung on the wall. To create the new design I used the Rhino commands Bend, Line, Surface, Extrude Surface, and Circle. Going from the previous iteration to the next, I once more realized the benefits of using digital design and 3DP technology. In this latest transformation, I was able to use commands in the 3D modeling software to manipulate the design rather than completely starting a new model from scratch. I was then able to fabricate the new product quickly using 3DP. Having the knowledge and access to these tools throughout the design process has greatly benefited this project. Overall, this product was not as successful due to scale. Although there are multiple hooks, the spacing and size of each are not sufficient enough to make the product functional. However digital design and 3DP could be used to inform and fabricate other, more satisfactory products.

Product 32

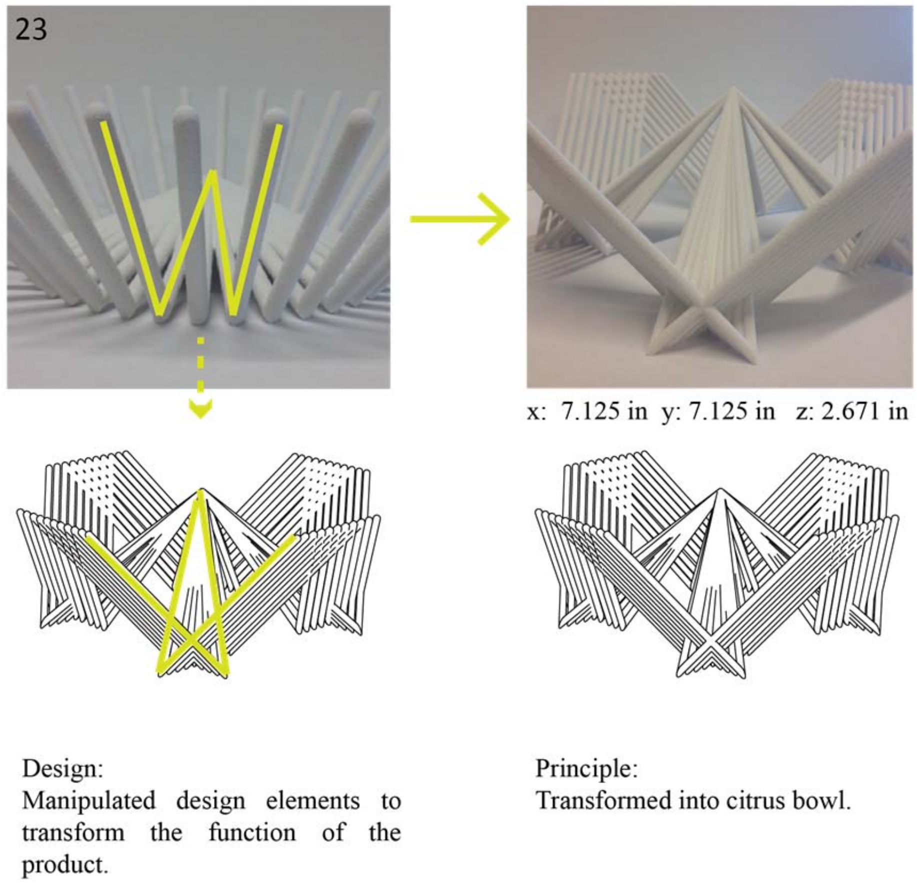


Figure 44. Product 32 Design Process

In the final product of the iterative design project, I transformed Product 23 into Product 32. To begin this design process, I identified the goals I wanted to achieve in the last product iteration. As I had had some successful fruit vessels emerge out of the first few stages of the project, I wanted to create a new vessel that incorporated what I learned in those elementary levels regarding designing a vessel to contain fruit. I strived to redesign Product 23 and intended to create a new vessel that was designed to specifically hold one type of fruit—in this case lemons. Conceptually the idea was inspired by the form of Product 23, as the shape reflected a citrus juicer. My intention was to expand upon this as well as compartmentalize specific areas in the holder for four lemons. I used the Rhino commands Line, Pipe, Rotate, and Mirror to model the new product. After creating the digital design, I was able to 3DP the new product and test it for fit, form, and function. The lemons fit well in each space, and the design utilized the advantages of 3DP as a fabrication method. Overall, the product was a success.

Conclusion: Phase I

Figure 45. Results of Iterative Design Project. Products 17, 25, 26, 29

In Phase I of the methodology, the project explored the use of 3DP in the product design process as an iterative design instrument, used as both a manufacturing and artistic means combining design and technology. The purpose of the experimental project was to gain a critical understanding, explore the potential, and experience how 3DP could be incorporated into the design process. Utilizing 3DP throughout my design process has empowered me to test of all my ideas, rather than a select few allowing the analysis and synthesis stages of the design process to be explored simultaneously. Through the integration of 3DP, I was able to realize new design possibilities beyond the original precedent.

As part of this project, I expected to gain a better understanding of how and when to use 3DP in the design process and some of its constraints as a fabrication method. The project was designed to utilize 3DP to print and test full-scaled models of each product throughout my design process. However, by doing this, I realized that there were some iterations that either did not need to be fabricated via 3DP or at least not at full scale as the cost outweighed the benefits of what I was able to learn from the printed product. 3DP enables designers to quickly test ideas early and throughout the design process, but understanding how and when to use 3DP would ensure that the benefit would be greater than the expense. For example, conceptual ideas could be explored using scaled models rather than potentially expensive full-scale models. Also simpler designs could use an alternative fabrication method to test scale, proportion, and function. Using 3DP throughout this project enabled me to realize that although it was a beneficial tool in my design process, it does not have to be the only one. The designer must be informed to make that decision in his/her design process depending on the project.

The results of the project led to numerous potentially successful new product designs, as well as an enhanced understanding of the capabilities and constraints of 3DP in the design and production process. In particular, Product 17 was found to be a new, innovative and viable product due to the successful confluence of the design principles axis, symmetry, hierarchy, rhythm, and repetition. These were illustrated in the redesign of the product, its successful functionality as a fruit vessel, and above all the use of 3DP as a means to fabricate this complex form. Product 25 was another successful outcome of this project. This new product design smoothly passed through the iterative steps to emerge as a new, functional vase that utilized 3DP as a means to fabricate the patterned, intricate form. Product 26 and Product 29 were also transformed into attractive pendant lights as a result of this project. Product 26 relied on 3DP as a fabrication method capable of generating a design with a complex pattern wrapping three layers to create the final form. The detailed piping increased in diameter from the outside to the inside, making the crafting of this light by other fabrication methods nearly impossible. Finally Product 29 could be considered yet another gratifying outcome of this iterative design project. Not only was the product successful as a unique and functioning light, throwing effective light and shadow patterns, but it also was a result that utilized several of the prominent advantages of 3DP as a manufacturing process. The intricate pattern, details, and connections in the design demonstrate the advantages of 3DP as a fabrication method of complex forms, as well as the simple fact that this method requires no additional assembly aside from adding the light bulb and cord.

Overall, the worthwhile as well as the less encouraging products resulting from this project have illustrated how 3DP could be used as an iterative design tool. 3DP was used as a tool to explain the results of the design process. 3DP became integrated into the design process such as traditional drawing has been used in the traditional design process, where a drawing is done to not just communicate ideas with others, but also as part of the design thinking process (Lawson, 2006). Through 3DP, I was able to communicate my own design thinking process, and through each new 3D printed product I was able to improve the conversation of the process and overall project. The results garnered from this project should help to illustrate how designers using 3DP can go from idea to fabrication in far less time than by other methods, often in less than 24 hours, link conceptual design to real world manufacturing, and rapidly generate products while exploring new variations in their representation and design. The information learned from this experiment will also contribute to the further development of the 3DP design process guidelines (see Appendix B) that were used as a resource in the 3DP Product Design Workshop in Phase III.

Phase II

Phase II continued to explore the impact of 3DP in the product design process, but through a collaborative, applied creative research endeavor with a fellow graduate student. In this project, 3DP was applied in both the design process and as a final fabrication method for a stool prototype. The purpose of this project focused on 3DP as a way to develop concept models, to test parts, to test materials and their properties, and to print scaled models. Another objective of this phase was to explore the use of third party printing services such as Shapeways and understand better how 3DP can be incorporated into the final design of a full-scale prototype.

This phase of the methodology began with the intent to incorporate 3DP throughout the design process—from concept, to design development, to final fabrication. The goal for both project collaborators was to strengthen their independent research. Therefore the design concept stemmed from the collaborators' research, and the execution of their design procedures arose from my desire to learn more regarding the potential of 3DP in the design process. To start, precedents from the collaborator's home country of El Salvador were analyzed through a Design Matrix developed by the collaborator for her thesis research.

Figure 46. Precedents for Phase II. Toys from El Salvador

The team used the Design Matrix as a tool for design to unite both methods of fabrication, craft-based as well as digital fabrication as well as to decompose the precedent shapes into points. The shapes were then taken out of the gestures created in the second phase and later re-located in a chart with the principles and elements of design. New shapes were then identified in Rhino 3D modeling software. These shapes were then manipulated to become modular components that could be put together to form the overall shape of the stool. The individual modular units, as well as other concept models were 3D printed to further examine shape and explore different modular combinations.

Figure 47. 3DP Process and Conceptual Models in Phase II

Using the 3D printed concept models, the team was able to realize and visualize design ideas and forms. Various modular combinations were examined before the team decided on a final form that emphasized the modular unit and fit within the design criteria of the Design Matrix. Having physical representations of the design ideas also helped the team discover how to incorporate 3DP into the final fabrication of the stool, which was one of the initial goals of the project. The team realized that when the modular pieces combined, unique angles were formed where structural joints were needed.   Finding pre-manufactured joints would have been impossible, so the team focused on incorporating 3DP in the joinery of the stool, utilizing the fact that 3D printed products can be customized. The team then designed the stool and joints in Rhino, and 3D printed the joints for the scaled model. Using the digital model as a guide, the team tried to assemble the scaled model using 1/8 inch diameter wooden dowels and the 3D printed joints.

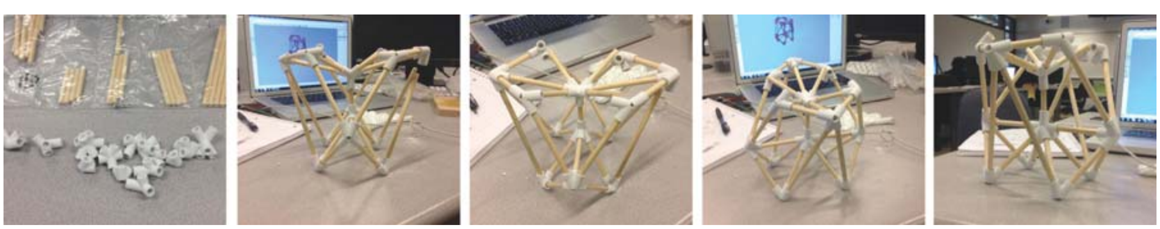


Figure 48. Scaled Model with Dowels and 3D Printed Joints

After attempting to put together the scaled model, the team realized that some of the joints that they thought were copies of other joints were actually mirrored, and therefore needed to be reprinted. Initially four copies of the same joint were printed rather than printing two from the top right and two from the top left. Having the 3D printed joints and the dowels to analyze physically enabled the team to have a better understanding of not only how the prototype should be assembled, but also how the joints should be altered in length to cover more of the wooden dowel and to add structural strength.

Figure 49. Various Test Joints. Left SLS Nylon. Right ABS Plastic

The next steps in moving forward in the design process were to explore materials. It was necessary to investigate how different materials reacted to strength tests and determine how different wall thicknesses of each material affected its strength. Knowing that the zcorp 3D printer in the Interior Architecture Department that used gypsum powder would not be structurally sufficient in strength, the team printed test joints in ABS (Acrylonitrile Butadiene Styrene) plastic using a MakerBot Replicator II located in the UNCG library and ordered test joints from Shapeways in SLS nylon. Three thicknesses (.125 in, .2 in, and .25 in) were printed in both materials, and after I conducted a strength test by placing my full weight on each printed piece it was determined that the SLS nylon with a thickness of .125 was both structurally strong enough and would be more cost-effective to 3D print. This testing step was critical not only for the project's progress, but also for gaining experience with working with a third party printing service, as well as experimenting with multiple materials.

The full scale 3D printed joints were then ordered from Shapeways in SLS nylon; meanwhile the team cut the dowels and tried different weaving patterns for the seat so that it would be ready for immediate assembly upon arrival of the joints. After the joints arrived, the team decided to experiment with adding color to the joints, which would correspond to the use of color in the precedents as well as emphasize those parts of the stool that were digitally fabricated. Using Rit Dye, the team was able to dye the joints a rich bluish-purple that would stand out against the lightly stained wooden dowels. Epoxy was applied to add structural strength to the final product. Once the stool was assembled following the digital model, the seat was woven onto the structure using a natural cotton rope.

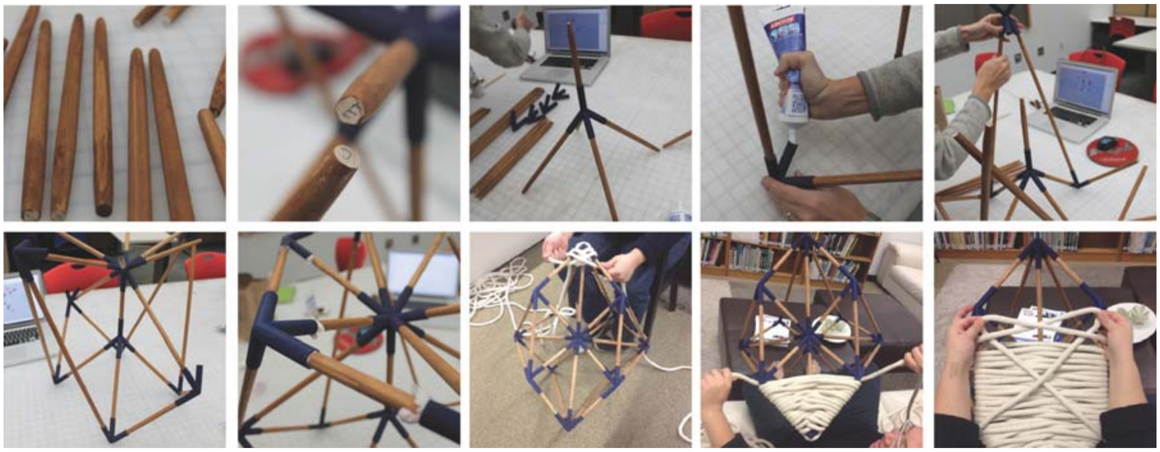


Figure 50. Process of Phase II Project Assembly and Seat Weaving

Figure 51. Final Fabricated Stool Prototype

Conclusion: Phase II

Overall the stool proved practical and sufficient as a seat, and also as an experimental means to integrate traditional and digital fabrication techniques. The 3D printed joints were essential to the design of the final product, as well as in the design process of the piece of furniture. 3DP allowed for each joint to be customized and was a fast manufacturing method in comparison to using an injection mold. 3DP also enabled the team to investigate design concepts in the design process beyond their initial idea by allowing the team to test and manipulate design combinations in the conceptual stage, as well as come up with a design that pushed the boundaries of traditional manufacturing. Incorporating digital fabrication enabled fabricating a design that would have been very difficult, if not impossible, to complete within the semester's time limit. Being able to incorporate 3DP into the final prototype enabled the team to push the design to farther limits.

One important aspect of this phase in the methodology was the utilization of a third-party 3DP company in our design process. Although 3DP technology has become more widely available, most individuals still need to use a third-party printing service such as Shapeways in order to gain access to and utilize 3DP in their design process or as a final fabrication method. These 3DP companies as well as other local tech shops have enabled designers, makers, or individuals to get involved in the Maker Movement and incorporate 3DP into their design process. Understanding and experiencing this process was important to my research and to the body of knowledge regarding the integration of 3DP in design.

There were, however, some cost issues with using 3DP that prohibited the team from producing more than one stool. The team would have liked to have made adjustments to the design of the stool, which occurred to them after the finished prototype was assembled. Some difficulties arose with keeping the epoxy to stay in the joints, and a new and better method of applying the adhesive could have been utilized if given the opportunity and resources to fabricate a new stool. Also, a structural element was removed from the stool after analyzing the scaled model as it did not appear to add significant structural support to the stool. Although the final stool was still structurally strong, the team thought that in future iterations the element should be included after all. The team also would have liked to have more time investigating the 3D printed components to see if there could have been a way to economize the cost by reducing the amount of material used. But due to the time lapse between ordering parts from Shapeways and receiving them (which was typically about 8 business days), this was not possible in order to finish the project in one semester.

Overall, the team and faculty advisors were pleased with the result of the stool prototype, and all considered the stool to be an effective first prototype using 3DP. The team hopes to continue developing this project, as well as pursuing other projects together. The team also appreciated being able to experience 3DP throughout the design process and as an integral part of the final fabrication of the prototype. This firsthand experience greatly enhanced my knowledge of 3DP and the ways it could be utilized in product design.

Phase III

In the final phase of the methodology, I facilitated a two-week long 3DP Product Design Workshop, in which a small sample size of undergraduate design students were asked to incorporate 3DP into the design process of an innovative new product. The students were randomly divided into three groups. Each group was given a different set of resources to help them utilize 3DP. Group 1 received a lecture and demonstration on 3D printing, as well as a set of 3DP Guidelines (see Appendix B) developed by me on how to incorporate 3DP into the design process; Group 2 received only the Guidelines; and Group 3 received just the lecture and demonstration. The aim of the workshop was to not only familiarize design students with 3DP, but to also analyze how design students with little to no 3DP experience would respond to the incorporation of 3DP in the product design process and how the various resources provided would affect their results.

Before the start of the workshop, the students were asked to fill out a survey regarding their digital proficiency in various topics, software, and technologies. The information provided by the students helped me gauge the digital proficiency of the undergraduate students participating in the workshop (see Table 1).

Table 1. Student Skill Survey on 3D Modeling and 3D Printing

Student Skill Survey administered at the beginning of the semester to analyze the varying levels of students' skills. Students were asked to indicate their level of digital proficiency in various topics/technologies. A.) Proficient B.) Comfortable C.) Familiar D.) Novice*

		3D Modeling	3D Printing
Group 1	Student (S) 2	B	B
	S 3	C	D
	S 4	D	D
Group 2	S 5	B	D
	S 6	C	D
	S 8	B	C
	S 9	C	D
Group 3	S 12	A	D
	S 13	B	D

*Four students did not take the survey that were involved in the workshop. S 1 from Groups 1, S 7 from Group 2, and S 10 and S 11 from Group 3.

The results of this survey indicated that a majority of the 13 participants involved had either little to no experience in 3DP or were not confident in their use of the technology. Their skills in 3D modeling, which is a significant element in being able to utilize 3DP, had a wide range of responses from proficient to novice, but a majority of the students considered themselves to be either comfortable or familiar with at least one 3D modeling software.

The project introduced in the workshop asked students to design and fabricate a new and innovative product of their choosing, using their preferred 3D modeling software. The plan was for the students to integrate 3DP into the design process, from the conceptual stages to the final prototype, with at least one printed model at each of the two presentations. Students were assessed using an evaluation questionnaire (see Appendix C) that I developed, which asked them to analyze their design process, their product and their use of 3D printing in the design process.

At the interim presentation, only four of the students had 3D printed models to present. Two students from Group 1, one student from Group 2, and one student from Group 3 discussed their concept, models, 3D printing, and the next steps in their process. There were two other students, both from Group 3 that sent their files to be 3D printed at the UNCG library using the MakerBot Replicator II. But due to high demand of the printer their files were not finished in time. They either did not have a model ready to be printed, or their print file was not readable by the 3D printer and could not be printed. The students that did not have interim scaled 3D printed models discussed their problems with using 3D modeling software programs.

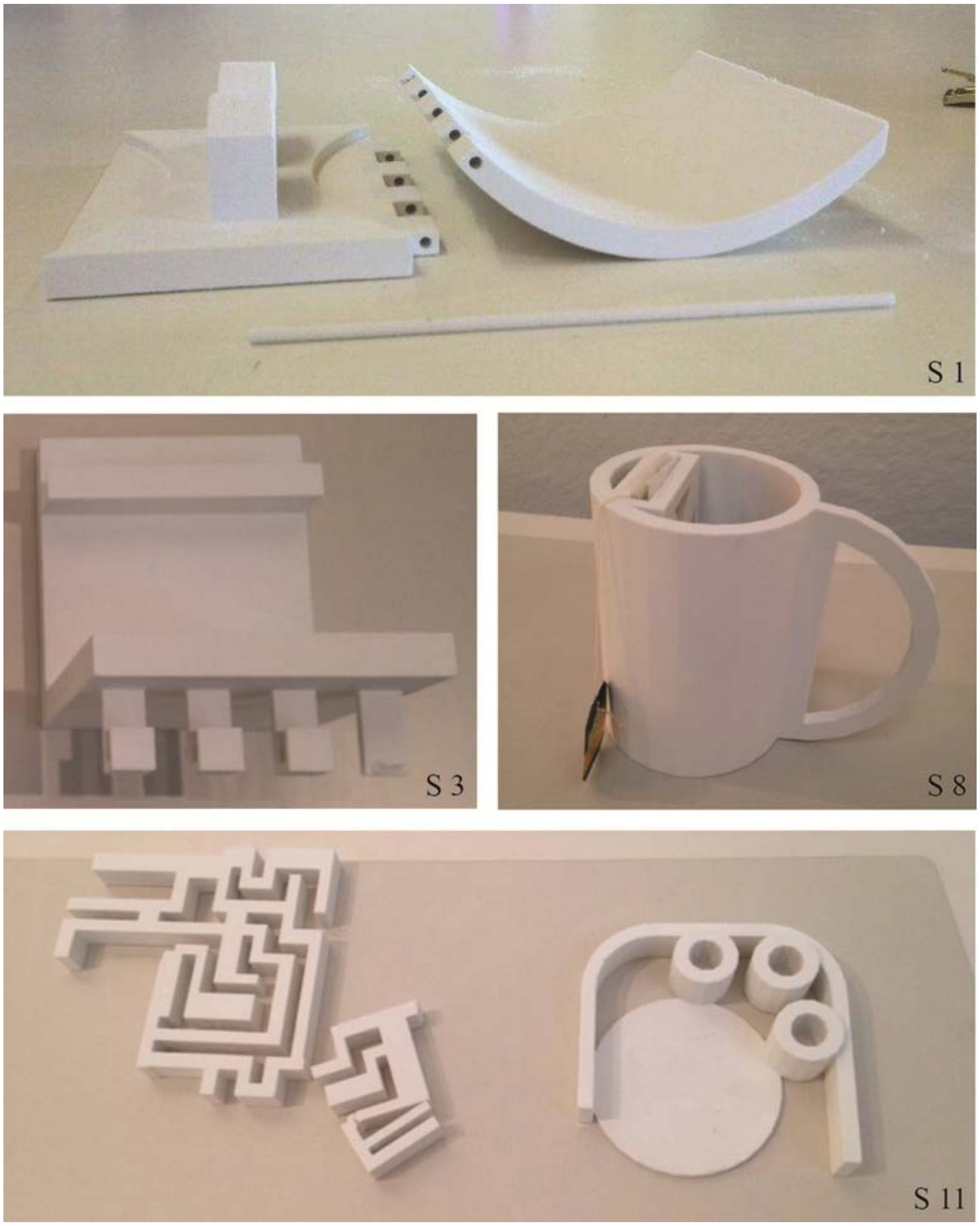


Figure 52. Images from Interim Model Presentations

The two students presenting from Group 1 (Student 1—S1 and Student 3—S3) had models with various design difficulties. S 1 presented a model of a covered toothbrush holder. The holder was to be wall mounted with a hinged protective cover that could open and close to gain access to the toothbrushes. The student 3D printed the holder, the curved cover, and the pin designed to go through the hinge to attach the cover. The model revealed that the holes in the hinges were too small to put the pin through, the slots for the toothbrushes were disproportionate to the size of both the overall holder and a standard toothbrush, and the curved top was not self-supporting and would rest on top of the toothbrushes when closed. She also needed to include a way to mount her product on the wall. Despite these shortcomings S 1 expressed that the 3D printed model was a fast and effective fabrication method to be able to physically see design flaws at the interim stage of the design process.

S 3 presented a model of a hook and shelving unit. The function of the product, a shelf, was to hold various objects on top while having hooks underneath to hold keys. The model presented had four hooks that were too close together to be functional, and the surface intended to hold objects was too shallow and underdeveloped as a design to be successful. The student expressed her issues with 3D modeling, stating that she had to change her design based on her lack of adequate modeling skills. S 3 also discussed the use of 3D printing in this stage of the design process. She noted that it was beneficial to have a 3D printed physical object to see that the product had scale and proportion flaws that she could analyze and correct. She could then make improvements as she moved forward with her product.

There were two more students that presented interim scaled models. S 8 from Group 2 displayed her model of a teacup with a built-in teabag compartment. The design was a typical mug shape with a slot inside for a tea bag. The design of the compartment, however, was too small to allow for various sized tea bags and was inadequate to hold a tea bag after it absorbed water. The student expressed her lack of modeling skills as a reason for the simple design, but hoped to move forward from the interim model with a focus on integrating the design of the tea bag compartment with the overall form of the teacup. S 8 appreciated having a 3D printed model, as she stated that it would have been difficult to fabricate this model using another method in the same amount of time. S 11 from Group 3 was the last to introduce a product at the interim presentation. Her idea was to create placemat connectors that would be used to create a physical and conceptual sense of connection at the dinner table. Her model was a geometric design that was supposed to interlock with other similar products. The idea of her product was questioned, and it was suggested for her to use her design as trivets that could be connected to fit various sized pots and pans. She explained that she had another idea for a product, but had issues with getting the file readable by the 3D printer.

Following the mid-project presentation, I spent the next class working with students individually on their design concepts and with 3D modeling. I also gave an impromptu Rhino3D demonstration on basic 3D modeling techniques, which was requested by the students. One conclusion drawn from this exercise was that the students' limited 3D modeling skills were an unforeseen obstacle within the workshop and proved to be an impediment with the results of the attempted products. I spent a few hours after class helping S 6 and S 9 from Group 2 and S 4 from Group 1 with modeling their products to be 3D printed.

Final Results

In the final presentation, each student discussed her product prototype. I have categorized the results in the following groups based on their 3D printed model's successes and/or failures: Design Complexity, Structural Integrity Failures, Issues with Scale/Proportion, Supports Mass-Customization, and Overall Successful Outcomes. Some of the students' prototypes fell in to more than one category.

Design Complexity

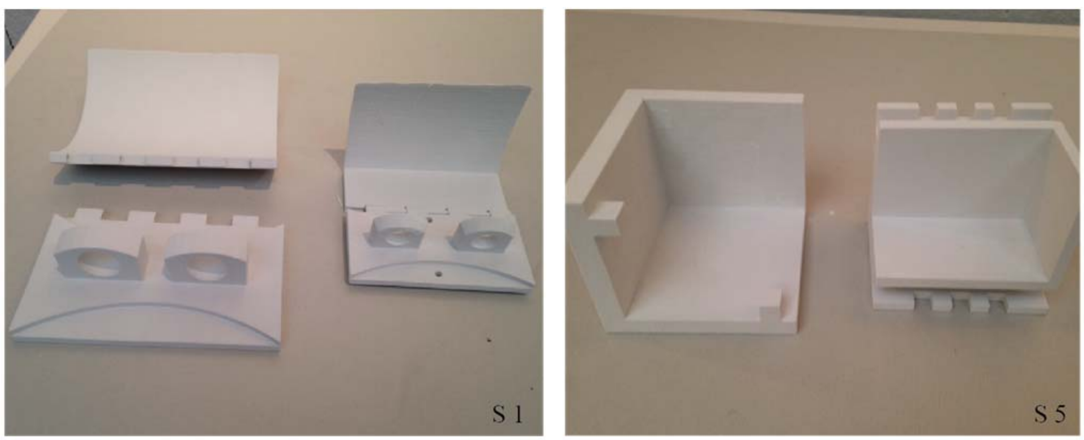


Figure 53. Design Complexity Results

An advantage of utilizing 3DP as a fabrication method and as tool within the design process is its ability to manufacture complex objects quickly and efficiently, as compared to other traditional methods. Only two students seemed to explore this resource in their design process and in the overall design of their newly created products. S 1 from Group 1 presented her toothbrush holder, which she was able to print twice during the course of the project. In the second printing the student printed the entire assembled product rather than in three pieces as she had done at the interim presentation. By printing a fully assembled hinged product, the student was taking advantage of another 3DP utility as a fabrication method, since there was no additional assembly required for the product to be functional. The product still had some design glitches that appeared after printing: if the product were to hang on the wall as intended, the cover would hit the wall, leaving little room for someone to remove or put back a toothbrush in the holder. The student commented on the value of 3DP in her design process in her self-evaluation, in which she stated that using 3DP helped her visualize the changes that needed to be made in the design of the product. She pointed out that 3DP enabled her to fabricate a fully assembled complex product that would have been difficult to manufacture otherwise in the given timeframe.

S 5 from Group 2 presented her Easy Store Travel Shelf, which comprised two shelf pieces that slid together to form a box for traveling. Although she did not present a model at the interim presentation, she was able to print a scaled version of her product before she printed her final. In her process she utilized 3DP to explore how the two shelves would fit together and learned what adjustments were necessary to make the final prototype. She used 3DP to print a complex form that she could test for its fit and function. In her self-evaluation S 5 analyzed her design process using 3DP and identified the benefits of having a quick fabrication method facilitating rapid design changes for complicated forms.

Although both students needed additional development of their design, they both began to understand and appreciate the advantages of using 3DP within their design process. As I attempted to assess why the projects by these students were more successful, I first reviewed their answers from the digital proficiency survey, which S 1 did not submit, but S 5 ranked her 3D modeling skills as a B. I spoke with S 1 after the workshop and she revealed that she had actually 3D printed once before for a different project. Another commonality that benefited their design process and their final outcomes was their use of Rhino 3D software, which has a wide variety of commands that aid a designer in creating complex forms. Overall, both students seemed to be more comfortable with 3D modeling and understanding how to utilize 3DP in their design process.

Structural Integrity Failures

Figure 54. Structural Integrity Failure Results

Throughout the course of the workshop it became evident that many of the other students lacked the 3D modeling skills needed to design products to be 3D printed. This lack of knowledge became clear through the number of students whose products had structural failures. S 2 from Group 1 presented a wall-mounted necklace “detangler” that had broken. Due to her difficulties with 3D modeling, her final 3D print was her only printed product of the workshop. She admitted her product had structural, scale, and proportion issues and missed the additional details that would have enabled the product to hang on the wall like it was intended. Overall, she felt limited in her design capabilities because she was unaware of how to model the product via the software she used.

S 4, who was also from Group 1, designed a to-go coffee sleeve, but had structural issues with one of her prints for the final that made her print again. The handle to the sleeve had broken off, which caused her to have to reprint for the final display. I was able to inspect her file and could help her attach the handle so that it would not detach in the printing process. Her lack of modeling skills was evident in her simple design and need for additional help to fix simple model issues.

S 8 from Group 2 exhibited her idea of a teacup that had a built-in compartment for a tea bag. She printed two models of the product for her design process; however, both products had design and/or structural issues. The model for her final prototype was not modeled correctly to 3D print, so the sides of the teacup did not stay together once removed from the printer. In her self-evaluation, the student observed that using 3DP allowed her to realize the modeling problems of her product, which she felt improved her design process. Overall, the student seemed to have an appreciation of how 3DP could be beneficial in the design process; but unfortunately she did not appear to have the 3D modeling skills to be able to execute fully the process to her advantage.

The final student to demonstrate structural integrity difficulties with 3D printing models was S 12 from Group III. She presented her model of a customizable USB cover.

She attempted to print twice during the design process, but both of her printed models reflected her efforts to craft a successful print rather than using the process for investigating form and function. Neither of the models successfully printed due to the lack of thickness of the surfaces used in the model, which made it difficult to further analyze the prospects for the product. The student further elaborated on her struggles, which included her insufficient modeling skills, a major inhibitor in achieving success in this project. She concluded that 3D printing was not too difficult, but 3D modeling was. The student's use of 3DP in her design process was limited by the fact that she was unable to 3D model well enough to be able to learn from her 3D printed models.

Assessing the students who offered models short on structural integrity related to a commonality fundamental to each of the students, which was their lack of 3D modeling skills. The students either were not familiar in general with 3D modeling, or struggled with understanding how to prepare the 3D model in order to 3D print the product, which could stem from a lack of understanding of how to prepare a model for the real world that could stand the test of gravity. In either case, each of the students critiqued their 3D modeling deficiencies in their self-evaluations. A revealing result generated by this analysis of the workshop and student self-assessed 3D modeling "grading" is that three out of the four students ranked their skills with a B or higher, which leads me to conclude that the students struggled with understanding how to model in preparation for 3D printing.

Issues with Scale and Proportion

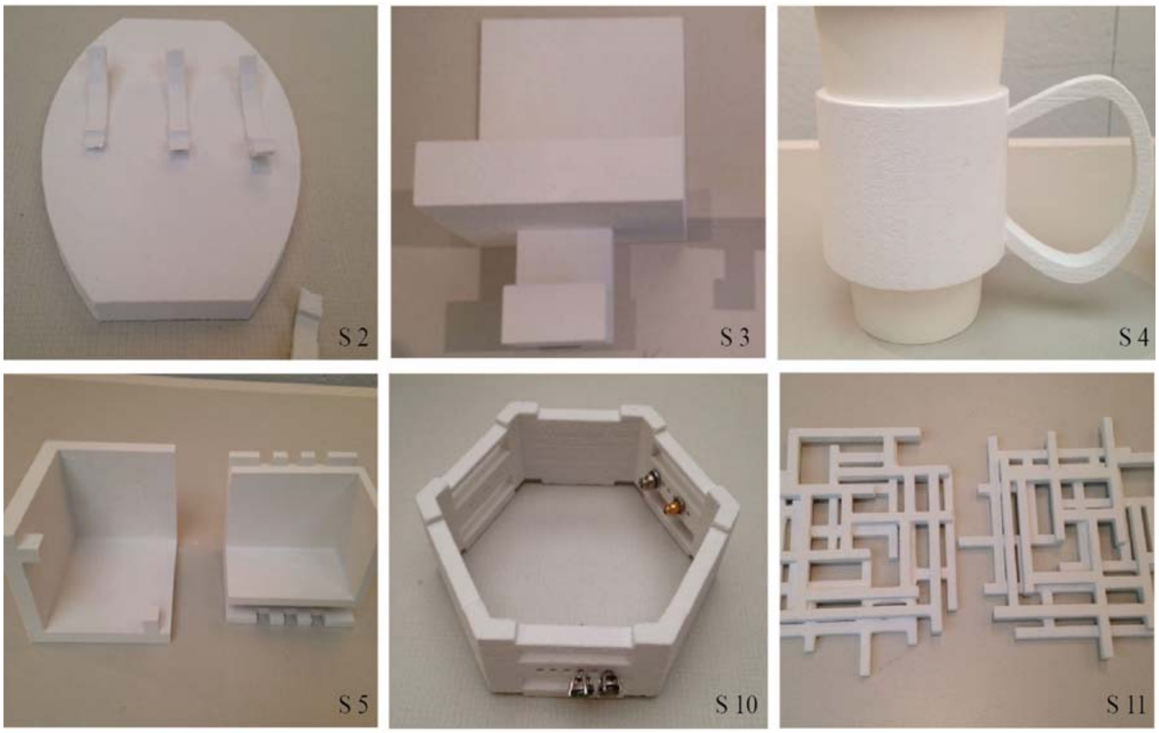


Figure 55. Issues with Scale and Proportion Results

One of the foremost struggles the students encountered was understanding scale and proportion in their product's design. This realization was revealed through testing their physical models. S 2's jewelry detangler not only fell apart after printing, but also had many scale and proportion issues. The hooks were too small and too close together to be functional, and the back plate of the product was much thicker than it needed to be. S 2 would have benefited from further design development and examination of her product. S 3 from Group 1 discussed her multifunctional shelving unit prototype. Taking advantage of one of the benefits of 3DP, the opportunity to model and print multiple times during the design process, allowed her to make adjustments to the design based on reviewing each previous print. In her first iteration, she encountered scale and proportion issues with the hooks on the bottom of the shelf as well as with the overall shelf. S 3 reevaluated her design to adjust for these issues. However, she ended up overcompensating, going from hooks that were too close together and too small to be functional to creating one large hook that was too big to hold keys, as she originally intended the design to do. Overall, the product needed to pass through even more iterations before it would be deemed functional, but there were evident improvements over the first and second versions. S 3 critiqued her work and the use of 3D printing in the design process in her self-evaluation, in which she stated that using 3D printing made her aware of necessary alterations for her product; however, due to time and resource constraints, she was not able to implement them.

S 4 also struggled with scale and proportion issues with her design of the to-go coffee sleeve. The handle was much larger than it needed to be, and it lacked design innovation and integrity to become a viable product. The disproportionate handle was revealed after printing the product, which a user could hold and inspect to realize its flaws. Although creating a more complicated form, S 5's product had some scale and proportion issues that made its functionality less satisfactory. The product was too small to function as a shelf or a box, but the student was able to utilize 3DP to assess fit, but was not able to develop a product that was scaled correctly despite her being able to print twice during the design process.

S 10 from Group 3 showed her model of a modular, stackable jewelry holder that was as wearable as jewelry itself. The product, although functional and certainly intriguing, needed further exploration and modification. The product disclosed both scale and proportion issues, with the holes for earrings being too close together for each of them to be functional. The use of 3DP in her design process was not fully exploited because she was unable to make modifications past her first print, which served also as her final prototype. Successive iteration is one of the most valuable features of 3DP. When S 10 discussed using 3DP she talked about her problems with scale that appeared with 3DP. But she also observed the efficiency of 3DP as compared to other fabrication methods when needing to analyze and evaluate a model quickly. In her case the product needed to be contemplated and worked out more carefully to be successful. 3DP could have been better utilized throughout the design process by testing fit, form, and function earlier in the process when these factors first came into play.

Finally S 11 also experienced issues with scale and proportion in her products. She presented her model of a trivet. She was able to display models in both of her presentations, which helped her in the design process by enabling her to evaluate and make alterations in the design development of her product. However, her changes focused on the design and not the overall scale. The trivets were too small and did not connect together successfully as the design intended. Both models needed to be further developed and tested in terms of scale and fit in order to produce a more viable and better thought out item.

By analyzing the results of this group, I could determine that the students' struggle with scale and proportion stemmed from two components: Limited timeframe to fully develop fewer iterations of their products and a lack of overall product design experience. Within an interior architecture program, students do not all take the same studio courses, resulting in students gaining various experiences in their different fields of design. However, as I did not survey the students on their product design experiences, I am not able to confirm this conclusion. The other aspect that I suspect affected these results was the limited timeframe, since I can infer that with more time students could have further explored designs that confronted their scale and proportion issues and might have been resolved more satisfactorily.

Supports Mass-Customization

Figure 56. Supports Mass-Customization Results

Another aspect of 3DP that I introduced to the students in my demonstration and in the 3DP design guidelines was the concept of mass-customization. A majority of students did not integrate this feature of 3DP into their design concepts, but three students explored it through their products. S 7 from Group 2 designed a multipurpose wrist holder that was supposed to increase the productivity of the user. Although her product had design and functionality issues, and her final model appeared more as a concept sketch rather than a working prototype, her design concept was intriguing. The intent was to design the bracelet specifically for the user's needs, thereby incorporating the concept of mass-customization. However, her design did not focus on one specific type of user and she did not create a useful product prototype. When reflecting on her use of 3DP in the design process, she stated that it allowed her to assess the reality of scale, rapidly construct a prototype without a need for additional joinery, and also to see potential failure quickly, before going too far along in the project.

S 9 from Group 2 also focused her design on the idea of mass-customization, as she displayed her model of a matrimonial ring stand. Her product was designed to be a place to store wedding rings while performing tasks that could cause risk to the rings. Her product form was a tree, which not only served a function but also symbolized her own partnership.   Although successful in its intended function of holding rings, it was not satisfactorily developed in its design or concept. The branches of the tree should have been customized and designed more purposefully to specifically hold each partner's ring,. Although her design could have been more developed, she concluded that the ability to mass-customize via 3DP was an important advantage for marketing her product, since she wanted to design and customize matrimonial ring holders representing a particular couple's special relationship. Overall, her intention for designing a product to utilize the advantages of 3DP was quite good; however, she focused less on incorporating it into the design process than as a final fabrication method.

Finally S 13 from Group 3 also experimented with the principle of mass-customization in her product's design. This student presented two models of a Vessel Design Assistant, which was a non-disposable product that would eliminate waste in the floral design industry, while aiding floral designers with floral arrangements. One product was a Vessel Design Assistant to fit standard vase sizes and was printed in ABS plastic at the University library; the other was a design of the container and the Vessel Design Assistant. Although both products needed further work, in her self-evaluation she elaborated upon the benefits of being able to customize the product based on the size of a vase and to test the product for function immediately after printing.

Each of these students incorporated the concept of mass-customization through 3DP into the designs of their products. Although none of the students pursued customizing and producing their products beyond the classroom each seemed to have acquired an understanding of this 3DP feature. It should be added that of this student group two were graduate students. These students had a greater appreciation and understanding of the impact of 3DP as a design tool and fabrication method. The process necessitates a more advanced comprehension of how the technology could affect manufacturing. This type of big picture thinking is a skill emphasized in graduate school, but not familiar to the average undergraduate.

Overall Successful Outcomes

Figure 57. Overall Successful Outcome Results

The final section assessed the overall success of the results. Although no student had a product without flaws, a few students ended up with products that adequately demonstrated the use of 3DP in their design process, while another had developed a product that was conceptually strong and generally functional.   The two students that seemed to have a more advanced understanding of how to integrate 3DP in their design process were S 1 and S 13. S 1 printed twice through her design process and through her interim model, she explored fit, form, and function of the various elements in her product, which informed and improved her next iteration. She then investigated the ability to 3D print a fully functional product without any additional assembly, which is one major advantage of 3DP as a fabrication method. S 13 was the only student able to experiment with multiple 3D printed materials with her models. Overall she seemed to comprehend ways to use 3DP in the design process by not only testing various materials, but also testing functions and exploring forms. She also understood 3DP's ability to mass-customize, which she utilized in her product's concept. S 6 from Group 2 developed a

Sphere Music Amplifier, which was conceptually strong and functioned well. Although there were some issues with fit as most cell phones are too large to slide into the bottom of the product as the design intended, the design was unique and utilized 3DP as a fabrication method. These students' abilities and performances were also recognized by their peers, who ranked them 2, 4, and 1 respectively. (See Table 2)

Conclusion: Phase III

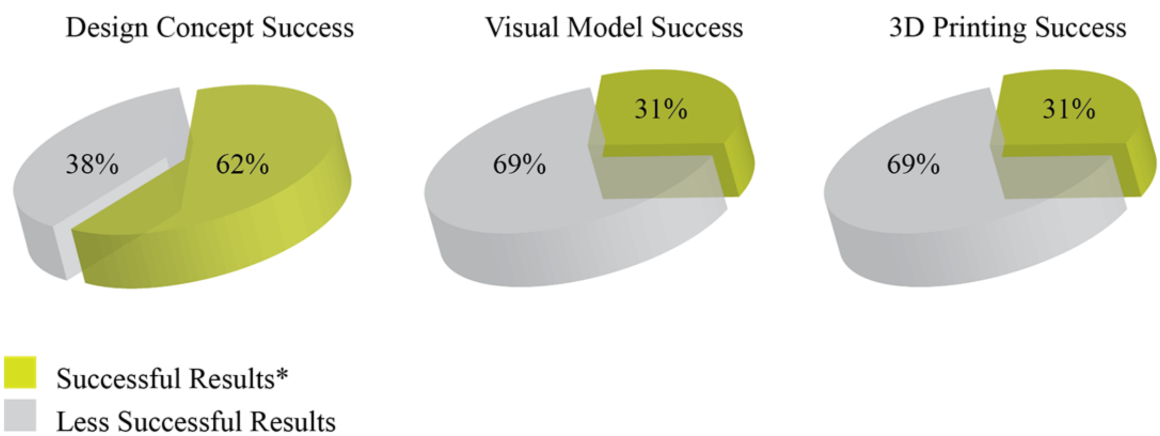
Table 2. Quantitative Results from Phase III

Students	3D Modeling*	3D Printing*	3D Modeling Software	Interim Model	Final Model broken	Discussed Modeling issues	Concept Rank**	Model Rank**	3D Print Rank**	Total points	Quantitative Rank
S 1			Rhino	●	●	●	4.2	4.4	4.4	13	2
S 2	B	B	Sketchup	–	●	●	4	3.3	2.6	9.9	13
S 3	C	D	Sketchup	●	–	●	3.8	4.3	3.5	11.6	9
S 4	D	D	Sketchup	–	–	–	4	4	3.6	11.6	9
S 5	B	D	Rhino	○	–	–	4.6	4.3	4	12.9	3
S 6	C	D	Rhino	–	–	●	4.6	4.4	4.4	13.4	1
S 7			Rhino	–	●	●	4.6	3.8	3.8	12.2	6
S 8	B	C	Sketchup	●	●	●	4.4	3.8	3.6	11.8	8
S 9	C	D	Rhino	○	●	●	4.2	4	4.2	12.4	5
S 10			Sketchup	–	–	●	4.3	4	3.8	12.1	7
S 11			Rhino	●	–	–	3.5	3.7	3.8	11	11
S 12	A	D	Sketchup	–	●	●	4.3	3	2.8	10.1	12
S 13	B	D	Rhino	○	–	–	4	4	4.7	12.7	4

Red = Group 1, Blue = Group 2, Green = Group 3
*self-ranking grades from survey given at beginning of semester on proficiency
**Average of points from self and peer-evaluation questionnaires (1-5)
Pink box relates to answers from Evaluation Questionnaires

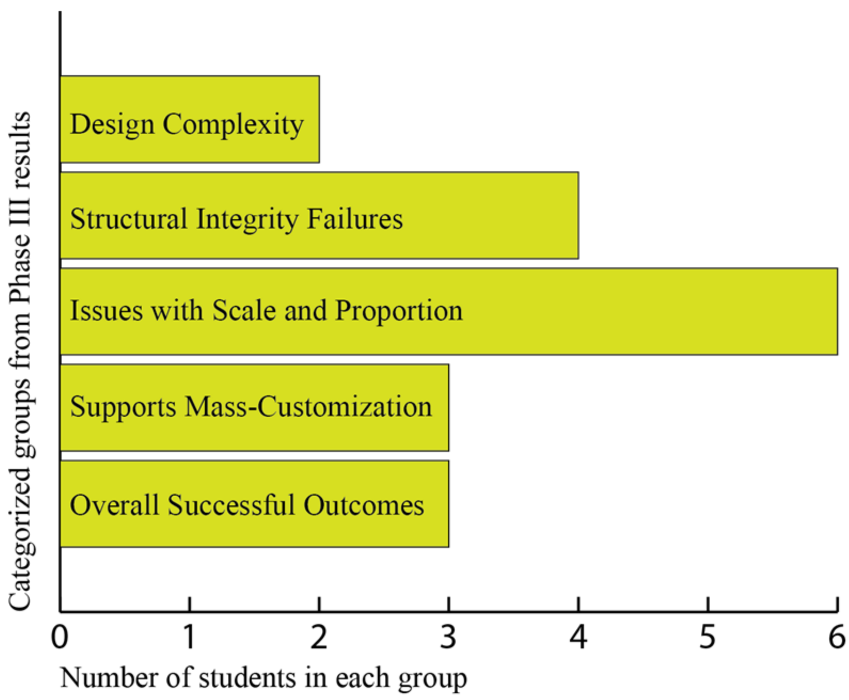
● Yes
○ Yes, but not at interim presentation
– No

Table 3. Graphical Quantitative Analysis



*Success percentage determined by the number of students with quantitative marks above 4.2 from Table 2

Table 4. Results from Categorized Groups



Although every student had the opportunity to use the 3D printer in Phase III, only a few students came away from the exercise truly understanding how to exploit the features of 3DP in their design processes. In analyzing the results, it is most important to note the initial survey given at the beginning of the semester, in which the students rated their proficiency in both 3D modeling and 3D printing. The class self-ranking in 3D printing proficiency was predominately novice, with majority of the students ranking their pre-knowledge of 3D printing with a D grade. Moreover, the class rating for 3D modeling was averaged to be between a B and C. This acknowledged lack of knowledge with 3D modeling was evident throughout the workshop, as students struggled with building models that could be 3D printed.

Another factor that affected the results of the workshop was the limited timeframe of the project. The project took place over a two-week period during which I expected the students to use the 3D printer at least twice, but preferably more frequently throughout the project. The workshop asked the students to design, develop, and fabricate a product using 3DP. With the lack of knowledge of both 3D modeling and 3D printing, students spent more time working on how to 3D model in preparation to 3D print than on developing their product and understanding how to utilize 3DP in their design process. All of the final 3D printed prototype models needed to go through further iterations to address design or functionality issues before being considered completed and viable.

Overall, according to students' self-evaluations, there seemed to be some consistent recognition of benefits—but also drawbacks—with using 3DP. The predominant obstacle seemed to be the students' struggle with 3D modeling, which was noted by nine of the thirteen students in their self-evaluation. The students stated that they spent more time trying to figure out how to 3D model their products than on designing them. One important idea to analyzing the results of this phase is to differentiate between the various levels of expertise in design thinking. According to Lawson (2005) there are five levels of expertise in design as mapped out by Kees Dorst (2003), and at each level a designer gains a better understanding of how to perform and analyze a certain task. Each level is acquired through knowledge and experience. Most of the students in this workshop were not as experienced with product design and 3D modeling to 3D print, which would place them between the novice and beginner levels of expertise. Their focus in the project was on the task and not the skill making it difficult for them to excel and problem solve, and in order for them to advance they need to progress their level of expertise in design. However, the experience for the students in this project can be viewed as a significant stepping-stone in their design learning.

Another drawback discussed was the size constraint of the print bed of the 3D printer. The students were told to limit themselves to designing and fabricating products that were approximately 4” x 4” x 4”, so concern over print bed size should not have been relevant to this workshop. There also seemed to be some consistency and commonality with students perceiving the benefits of using 3DP. Most students mentioned the value of being able to have a physical 3D printed model immediately, which they then could analyze for scale and proportion to aid in their design process. Students also appreciated 3DP for its ability to rapidly prototype, although very few students seemed to take advantage of this benefit. Generally and optimistically, most students seemed to develop at least a basic understanding of both the benefits and drawbacks of 3DP, but were incapable of fully incorporating 3DP in their design process due to the limited time frame and their limited modeling skills.

In conclusion, the elements that affected the outcome of the workshop the most were the lack of 3D modeling skills of the participating students and the limited timeframe of the project. These factors are important to my research investigating the impact of 3DP in the design process, as these results reflect the capabilities and potentials of current design students to utilize 3DP in their work. In regards to the guidelines developed as a resource for this workshop, these were underutilized as an aid, since these guidelines were designed for individuals that already had some understanding of how to 3D model in product design. The participating students needed a resource that introduced them to the process of modeling for 3DP rather than a set of guidelines that illustrated how and why to use 3DP in the design process. Based on the results of this workshop, I can infer that the students and designers that will gain the most from integrating 3DP in their design process, as well as those able to use the developed guidelines, are individuals who already have some experience in 3D modeling for product design. Those with some familiarity with modeling will then be able to utilize the guidelines to help them make informed decisions on how and why to use 3DP in their design process, or even as a final fabrication method. Further discussion regarding the next, future steps in this research is provided in the Conclusion of this thesis.

CHAPTER V

CONCLUSION

This thesis investigated the role of 3DP in the design process of interior products through three methodological phases following research on the Maker Movement, 3DP, and the product design process. The research, both through reviewing literature on the subject and practical applications, focused on gaining a first-hand experience and critical understanding of the technology's capabilities and limitations. Throughout this study my attempt was to integrate 3DP into the product design process, particularly through exploring the intersection of design, technology, and art in product design. (See Appendix D for images of body of work) The thesis also sought to observe and analyze how design students would incorporate 3DP into their design process through the 3DP Product Design Workshop.

Understanding the advantages and disadvantages of 3DP allowed me to utilize 3DP as more than an instrument for fabrication. 3DP also served as a vehicle to express and drive creative ideas. Incorporating this technology throughout the design process led to novel and innovative results beyond the initial ideas as illustrated in Phase I of the methodology. 3DP also enabled me to test, analyze, and evaluate each new idea enabling the analysis and synthesis stages of my design process to be integrated rather than sequential. Through the use of 3DP, I was able to conceptualize the realization of new design possibilities in interior product design. In developing my own body of work, I have applied 3DP, and with little to no previous experience working in particular materials, I have been able to create designs in gypsum powder, ABS plastic, SLS nylon, ceramic, raw silver, raw brass, and stainless steel. However, one can conclude based on the results of each Phase that preparatory research and practical experience in using 3DP is vital to success in the utilization of 3DP in both the design process and the final fabrication method in product design.

Through this research, I was also able to determine that 3DP is a tool with limitations and disadvantages. For designers and makers, understanding 3D modeling and digital technology is a critical aspect in order to fully implement 3DP in their design process. Also 3DP is not always the best choice for fabrication or prototyping due to economic limitations, which became a concern after analyzing my own work and getting feedback from the students in the workshop. There are also print bed size restrictions with the current 3DP technology that can be a limiting factor when integrating the fabrication method in the final design of a product. Overall, there are factors that designers and makers need to understand and take into consideration when deciding how to utilize 3DP in their design process, and my research hoped to synthesize these factors through this thesis and the 3DP Guidelines developed by me when conducting this research (see Appendix B).

A significant, but disappointing finding in this study was the realization that the design students who participated in the workshop did not have the 3D modeling skills to be able to fully understand how to integrate 3DP into their product design process.

Although the students had been trained in various 3D modeling software, the students had primarily used it to create renderings for spatial design. Transposing 3D modeling to 3D print is a more complex procedure, which became evident in the 3DP workshop. When modeling a product for 3D printing, a designer must have an understanding of how the product is constructed and would hold up to gravitational forces in the physical world in order to model with the precision and detail needed in 3DP. The participating students seemed to lack this understanding and/or the skills needed to execute the design properly. Because the students let their modeling skills drive their design, the students were not able to fully understand how to utilize 3DP in their design process. One might conclude from this that undergraduate students would benefit from introductory instruction in 3D modeling for product design.

As a secondary consequence of this thesis, I developed a set of guidelines (see Appendix B) intended for use as a resource in the 3DP Product Design Workshop. I hoped to use these 3DP Guidelines to help design students familiarize themselves with applying 3DP to their designs. However, based on feedback from the students, most were not able to utilize the guidelines due to their lack of modeling skills for 3D printing. Although the guidelines included some modeling tips for preparing a file to be 3D printed, they did not include a section on how to perform basic 3D modeling commands. As a result, the current guidelines became a resource assessing my own research and 3DP design experience helping me to better analyze and express my results rather than a teaching tool for others to utilize, which was an unforeseen outcome in this thesis.

In continuing this research into the future, I would revise the guidelines and add a section on relevant 3D modeling, which is required to utilize 3DP effectively as well as add suggestions on resources for tutorials on various 3D modeling software. I would also like to test the guidelines with students or designers that have had at least some experience with 3DP in product design in order to get more realistic and informative feedback. Further research would also enlarge the test pool resulting in more valid data. An additional aspect that I would like to explore is modular products using 3DP. As with the current desktop size of most 3D printers, printing products in modular pieces has become a viable use of 3DP in product design. Finally, one factor that is important to note that was not a focal point of my thesis research is how through incorporating 3DP in product design; a designer can customize a product for a specific user. My research focused on understanding the fabrication method in the design process, in which I produced products that were shaped and formed iteratively and not by the requirements of a specific user. However, the knowledge gained from this thesis will enable me to further investigate these aspects of 3DP in the future.

Overall, important lessons were learned from the research and design work performed in this thesis that collectively contribute to the body of knowledge regarding 3DP. An extensive review of literature on the Maker Movement and 3DP provided a foundation for investigating the impact of 3DP on the design process. My work in Phases I and II provides examples of ways 3DP can affect the design process, illustrating both the advantages and disadvantages of current 3DP. Phase II also focused on analyzing the use of a third-party 3DP service into the design process and final fabrication of components for a full-scale stool. These companies are playing a vital role in the Maker Movement as they are enabling access to makers and designers to not only 3D print in their design process, but also to experiment with new materials and to design, fabricate, and share innovative new products. The thesis also investigated how design students incorporated 3DP into their design process, and although the results are fairly inconclusive, participating students have now been exposed to a new technology that will hopefully influence their future design work both in school and as beginning design professionals. The students also now have an understanding that in order to use and benefit from 3DP, one needs to have more expertise in 3D modeling. This thesis was not able to fully address the impact of 3DP on product design due to the subject's breadth, complexities, and constantly advancing technology. However, as 3DP continues to progress, becoming more advanced, more affordable, and more available, this thesis can be viewed as an important early step in the advancement of understanding how 3DP can be incorporated into the design process of interior products.

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APPENDIX A

PRODUCT EVALUATION SHEETS FROM PHASE I

PRINTABLE PRODUCTS

Integrating the Maker Movement, 3D Printing, and Interior Product Design

Product Evaluation Sheet:

Date: Sept. 16, 2013

Day/Product #: 1

Cost: $18.43

Volume (cubic centimeters): 73.70 cubic cm

Print Time: 4 hrs 10 mins

Size of Product (inches): X 7.897 Y 7.762 Z 2.990

Ordering Principle of Design: Symmetry

Evaluation and Reflection (successes and failures):

To start, because the precedent's actual size exceeds the capacity of the 3d print bed, I chose to focus on the essence of the inital precedent, and use a scale that was appropriate for the 3D printing fabrication method. In the first level of iterations, my aim was to focus on symmetry, and due to the bilinear symmetrical nature of the precedent, I explored the vessel through radial symmetry. Overall, I kept similar lines, angles, and concept, but defined a central connection from which the product lines radiate. The exploration fo the ordering principle of design is successful; however, there are other factors that make this iteration as a whole not as successful.

3D Printing Role:

Evaluation and Reflection (successes and failures):

There were some issues with the 3D printing of this iteration of the vessel. For some unbeknownst reason, the printer added additional elements/binder as perhaps a means of additional support...? Unfortunately I'm not entirely sure; however, because of this the print did not turn out the way it was modeled. Also the legs could not support the vessel, but I'm not sure if that is because of the added material or their general lack of strength.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

Due to the failures of the 3D printing fabrication method, I am inclined to say that overal the product is not viable, despite the viability of the concept and the iteration involving the ordering principle of design, symmetry. The decreased scale of this iteration does change the initial function of the vessel from being able to hold 5 apples to only being able to hold approx. 2 or more of a smaller type of fruit.

Ideas for Redesign:

I do not think I will go further with iterations of this design due to its lack of viability; however, I do hope to learn from the mistakes that were made. First I'm going to focus on potentially rotating the object in the viewport, so that when it prints it will have the strongest part down; however, I'm not sure if that is what caused the added elements. Also I'm going to increase the strength of the legs of the vessel in other further iterations.

Product Evaluation Sheet:

Date: Sept. 17, 2013

Day/Product #: 2

Cost: $17.45

Volume (cubic centimeters): 69.80

Print Time: 3 hrs and 30 min

Size of Product (inches): X 6.25 Y 3.01 Z 2.927

Ordering Principle of Design: Axis/Symmetry

Evaluation and Reflection (successes and failures):

In this iteration, I am still focusing on the initial precedent, and evolving it based on axis/symmetry. Although the initial precedent emphasizes the use of an axis and symmetry, I wanted to explore another version of it, and looked at removing the top bars and repeated the base as the way for which it holds its contents. The vessel is a good representative of bilateral symmetry across a central axis; however, aesthetically, I feel it loses some of its unique qualities of the original.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method. The vessel is structurally sound and connects throughout the product to be strong enough to support its function. However, there are some size constraints with using our z-corporation gypsum powder 3d printer, and I feel that the vessel overall is too small in its length in comparison to its width and height; however, there could be changes made within the current size restrictions of our 3d printer to have it be a more successful product.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, I believe the product is too small proportionally. Also I feel some of the unique qualities of the original precedent have been lost through the repetition of its base, despite (with size corrections) it's success as a functioning vessel. Although simplicity can certainly be functional and aesthetically innovative, in this case, I feel the simplicity does not correlate to a well designed and innovative product.

Ideas for Redesign:

Some ideas for a redesign of this iteration, I would focus on scale and proportion so the vessel would be able to hold more or larger objects. Also, I feel that the innovative qualities of this are lacking, and there is a better solution to how the product could serve its function other than just a repeated base. Perhaps creating more purposeful spacing or varying the size of the base would be an interesting exploration.

Product Evaluation Sheet:

Date: Sept. 18, 2013

Day/Product #: 3

Cost: $24.88

Volume (cubic centimeters): 99.52

Print Time: 6 hrs and 7 min

Size of Product (inches): X 5.25 Y 9.854 Z 5.001

Ordering Principle of Design: Axis/Symmetry

Evaluation and Reflection (successes and failures):

In this iteration, I am still focusing on the initial precedent, and evolving it based on axis/symmetry. I wanted to continue with the precedent's form, but investigate it with more organic elements, as well as, define the axis as an understood element versus a visible definitive. I also wanted to create symmetry in a less obvious way. Overall, I think the product as a means of illustrating axis/symmetry is very successful.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method; however, there are elements of the product that I would change to make it more sound structurally. The individual components are as small (.125 inches in diameter) as I'm willing to print, but there are areas of the vessel that aren't as supportive, and hence pieces that broke.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function and viability, I believe the product is successful. As a vessel the product functions well, and the size of the product is more successful. There are changes to the form and size proportions that I would like to explore more to maximize it's capacity. Also there are structural elements that I would change, and some aesthetic aspects that I would like to explore further, but as one of the first products away from the initial starting point, I am pleased with the result. It resembles closer my own design aesthetic, as I enjoy combining the geometric with the organic. I also appreciate the understood axis rather than a defined one.

Ideas for Redesign:

Some ideas for a redesign of this iteration, I would like to focus on form and proportion to explore how to maximize the capacity of the vessel. Also, I would make the individual components larger in diameter, and perhaps connect in more places, in order to make the vessel more structurally sound using the current fabrication method. Ideally there would not be the four connecting bars, I would want to explore having the ends be more free and not constrained.

Product Evaluation Sheet:

Date: Sept. 19, 2013

Day/Product #: 4

Cost: $30.29

Volume (cubic centimeters): 121.15

Print Time: 3 hrs and 30 min

Size of Product (inches): X 7.886 Y 3.5 Z 3

Ordering Principle of Design: Axis/Symmetry

Evaluation and Reflection (successes and failures):

In this iteration, I am still focusing on the initial precedent, and evolving it based on axis/symmetry. I wanted to interpret the form of the precedent through planes rather than just lines. The ordering principles of design, symmetry and axis, are well represented. The form is simple and interprets the form based on its overall qualities, as well as, focuses on some of the geometric shapes that are created through voids in the initial precedent, and recreates them as solid planes, while emphasizing a defined axis and symmetry.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method. The vessel is structurally sound and the two planes are thick enough to not be brittle, but thin enough to connect to the initial precedent's aesthetics. As I continue to investigate further iterations of this design, it will be interesting to push the structural capabilities of 3D printing as a fabrication method as I change the proportion of the planes above and below the axis; however, I will maintain the .25 inch thickness of the planes as I feel that is a success.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, I believe the product is too small. The size of the planes above the axis should be longer, in order to, increase the overall capacity of the vessel. Currently there are also only two "walls," which aesthetically I appreciate the solid and void aspect; however, it does limit some of the function. I am pleased with the overall design of the vessel. It's simple geometric shape is modern and sleek, and reflects my aesthetic as a designer.

Ideas for Redesign:

Some ideas for a redesign of this iteration, I would focus on scale and proportion so the vessel would be able to hold more or larger objects. I am interested in altering the size of the planes above the axis in order to increase its overall capacity. I may also investigate increasing the length. As I appreciate the overall form with it's simple geometric shape, I hope to continue to explore iterations, while keeping a similar overall aesthetic. Further iterations may include, but not limited to, increasing the number of planes, changing the angles, and changing the overall size.

Product Evaluation Sheet:

Date: Sept. 20, 2013

Day/Product #: 5

Cost: $40.56

Volume (cubic centimeters): 161.84

Print Time: 7 hrs and 1 min

Size of Product (inches): X 7.529 Y 7.529 Z 4.360

Ordering Principle of Design: Axis/Symmetry

Evaluation and Reflection (successes and failures):

In this iteration, I am still focusing on the initial precedent, and evolving it based on axis/symmetry. I wanted to interpret the form of the precedent using radial symmetry. I interpreted the precedent based on the geometric lines and angles, in order to, reform the vessel using radial symmetry. The form is simple using solid and voids to create the shape.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method. The vessel is structurally sound, and the intersection of the bars are strong. I would be interested to investigate the iteration without the top bars all the way around to see if the vessel were as sound.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, I believe the vessel is successful; however, I would like to investigate other iterations with less bars and connections. I appreciate the solid and void aspect to this design. The overall size is adequate, but it may be more effective functionally if it were rectangular instead of square, in order to, increase it's capacity.

Ideas for Redesign:

Some ideas for a redesign of this iteration, I would focus on changing the shape of the bars and testing angles and connection points to continue with the overall aesthetic of the solid and voids, but with more geometric interest. I would also like to try various iterations of overall form, perhaps more rectangular or more oval/circular.

Product Evaluation Sheet:

Date: Sept. 23, 2013

Day/Product #: 6

Cost: $42.55

Volume (cubic centimeters): 170.19

Print Time: 5 hrs and 54 min

Size of Product (inches): X 5.219 Y 9.144 Z 4.242

Ordering Principle of Design: Hierarchy

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on the my day 2 iteration, and evolving it based on hierarchy. I wanted to interpret the form based on shape and location hierarchy. I kept the same general pattern; however, I removed the lower legs and created the form based on ascending diameters of the bars from the outside in with the thickest and most prominent being in the center. This pattern certainly emphasizes hierarchy; however, I am still not satisfied with the overall form.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a fairly successful fabrication method for this vessel. The main "basket" of the vessel is structurally sound; however, the outside legs that extended to create stability were too brittle or thin and broke off. Despite the success of the partial print, I don't feel that this form is pushing the limits of 3D printing, and I would like to push the complexity aspect of this further to make 3D printing a more appropriate fabrication method for this vessel.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, I believe the size of the vessel is appropriate and is functional; however, due to the broken legs, the product is not functional as it is. In other aspects of the viability, I am not satisfied with the overall form; and feel that it is not as innovative as I would like, and have not decided whether I will explore further iterations of the vessel.

Ideas for Redesign:

Although I have not decided if I will explore other versions of this product, if I were, I would focus on the stability of it, as well as, the complexity in regards to making 3D printing the appropriate fabrication method. I would also work on balances the stability with the overall weight and proportion of the object. As it is currently, it is too thick in some parts and too thin in others, and I believe a happy median can be found through further iterations.

Product Evaluation Sheet:

Date: Sept. 24, 2013

Day/Product #: 7

Cost: $36.29

Volume (cubic centimeters): 145.15

Print Time: 7 hrs and 12 min

Size of Product (inches): X 7.955 Y 5.535 Z 3.982

Ordering Principle of Design: Hierarchy

Evaluation and Reflection (successes and failures):

In this iteration, I am still focusing on the my day 2 iteration, and evolving it based on hierarchy. I wanted to interpret the form based on shape and location hierarchy. I transitioned the pattern into planes with the center plane shapes being the deepest and largest. The hierarchy is relatively subtle, but successful. I would consider for further iterations making the hierarchy more prominent.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method for this vessel. It is structurally sound, and the geometry is expressed well using 3d printing. I might consider making the planes slightly thicker to create more stability. They are currently at a .2 inch thickness, and .25 may be better, especially if I make it larger.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, I believe it is successful; however, I would like to continue to explore scale and proportion of this vessel in order to increase capacity, maybe just making it longer. I also appreciate the simplistic geometrical design of the vessel. Although still worth further exploring, I feel this overall design is successful and viable.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on the scale and proportion of this vessel. I would investigate the overall form in order to increase its capacity. I would also like to investigate pushing the complexity of this design in order to utilize 3D printing as a fabrication method. I look forward to future iterations of this product.

Product Evaluation Sheet:

Date: Oct 2, 2013

Day/Product #: 8

Cost: $31.82

Volume (cubic centimeters): 176.76

Print Time: 5 hrs and 57 min

Size of Product (inches): X 5.773 Y 8.275 Z 3.775

Ordering Principle of Design: Hierarchy

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 3 iteration, and evolving it based on the ordering principle of design hierarchy. I wanted to incorporate the whimsy and apparent randomness of the day 3 iteration, while focusing on making it structurally sound and manipulating the form. The hierarchy is demonstrated through both size and location. The central intersections of the pattern on either side of the vessel, as well as, the increase in sizing of the elements from the inside out demonstrate the principle of hierarchy successfully.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method for this vessel. It is structurally sound, and the geometry is expressed well using 3d printing. I might consider pushing the limit of the 3D printer bed in order to increase the overall size of the vessel.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, I believe it is successful; however, I would like to continue to explore scale, proportion, and form of this vessel, in order to, increase capacity and improve the overall design and aesthetic. I removed the base from the previous iteration in hopes of increasing the capacity; however, although it is currently viable as a vessel, I would like to specifically focus on the overall form in further iterations.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on the scale, proportion, and form of this product. I feel the product has disconnect across its axis, and I would like to explore a connected transition from one side to the other rather than being joined by a void. I appreciate the varying levels of the geometric elements, and would like to exaggerate and explore that further in other iterations. Also the overall form is something that I would like to change as I explore different shapes.

Product Evaluation Sheet:

Date: Oct 3, 2013

Day/Product #: 9

Cost: $21.15

Volume (cubic centimeters): 117.52

Print Time: 4 hrs and 22 min

Size of Product (inches): X 6.897 Y 6.2 Z 2.750

Ordering Principle of Design: Hierarchy

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 3 iteration, and evolving it based on the ordering principle of design hierarchy. I wanted to push that iteration more toward the aesthetic of ordered chaos rather than just apparent random chaos. I took the same concept of connecting point with lines; however in this iteration, I focused on a new overall shape, and allowed the lines to intersect in only specific places. The hierarchy is developed in this iteration through the increasing sizing of the lines, and the placement of the intersections compared to the non-intersecting lines and then to the voids. Overall, I feel that the ordering principle of hierarchy is well represented, although subtle.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method for this vessel. It is structurally sound, and the geometry is expressed well using 3d printing. I might consider pushing the limit of the 3D printer bed in order to increase the overall size of the vessel.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, I believe it is successful; however, I would like to continueto explore scale and form of this vessel. I feel that the overall size could be increased, or aspects of the form could be manipulated in order to increase its capacity and therefore its viability.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on the scale and form of this product. I am pleased with design of this vessel; however, I would like to investigate the connection at the bottom of the vessel, as well as, exapnd the width of the vessel, while potentially decreasing the depth. I look forward to further iterations of this design.

Product Evaluation Sheet:

Date: Oct 4, 2013

Day/Product #: 10

Cost: $31.27

Volume (cubic centimeters): 173.72

Print Time: 7 hrs and 12 min

Size of Product (inches): X 9.523 Y 5.869 Z 4.754

Ordering Principle of Design: Hierarchy

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 4 iteration, and evolving it based on the ordering principle of design hierarchy. To push this iteration forward from the previous, I explored increasing the number of planes and their intersecting orientation. The principle of hierarchy is clearly defined through the intersection of the planes as seen in the front view of the vessel. The amount of the plane visible increases from the base to the top. Overall, I would say this is a successful depiction of hierarchy.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method for this vessel. It is structurally sound, and the geometry is expressed well using 3d printing. I might consider pushing the limit of the 3D printer bed in order to increase the overall size of the vessel.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, I believe it is successful; however, I would like to continue to explore scale and form of this vessel. I feel that the overall size could be increased, or aspects of the form could be manipulated in order to increase its capacity and therefore its viability.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on the scale and form of this product. I am pleased with design of this vessel, and a particularly like the geometric angles that are formed through the intersection of these planes. I would like to push these connections further, and focus on creating more angles and vessel dimension through theses intersections. I look forward to more iterations with this design.

Product Evaluation Sheet:

Date: Oct 7, 2013

Day/Product #: 11

Cost: $47.46

Volume (cubic centimeters): 263.65

Print Time: 6 hrs and 45 min

Size of Product (inches): X 9.859 Y 6.899 Z 5.221

Ordering Principle of Design: Hierarchy

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 4 iteration, and evolving it based on the ordering principle of design hierarchy. To push this iteration forward from the previous, I explored increasing the overall size of the vessel, which was the biggest negative of the previous iteration. I focused on emphasizing hierarchy through size and location of the planes across the axis, in which the is a dominance above the axis versus below. This was not only effective in reflecting this principle, but it also helped correct the previous vessel's lack of overall capacity.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method for this vessel. It is structurally sound, and the geometry is expressed well using 3d printing; however, the overall design is simple, and 3D printing is not necessarily the best means for final manufacturing; however, it is an effective way to prototype, as well as, quickly iterate the desired design.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, I believe it is successful as the capacity has increased. I also consider the product to be viable in terms of the overall aesthetic and design. I am pleased with the design; however, due to the lack of sides, it makes the function somewhat limited to some.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on continuing to explore the simplicity of the design, but perhaps in changing the shape or the form or pushing the limits of the 3d printing in how thin the product walls could be.

Product Evaluation Sheet:

Date: Oct 8, 2013

Day/Product #: 12

Cost: $33.53

Volume (cubic centimeters): 186.30

Print Time: 7 hrs and 24 min

Size of Product (inches): X 7.229 Y 7.229 Z 4.249

Ordering Principle of Design: Hierarchy

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 5 iteration, and evolving it based on the ordering principle of design hierarchy. To push this iteration forward from the previous, I explored creating the angles and lines of the design through the use of planes versus rods. I wanted to continue to explore the geometric angles and shapes through the intersection of the planes. In terms of evaluating the success of the use of hierarchy, the design emphasizes hierarchy as defined by the elements above and below the central point/axis. The hierarchy is subtle, but overall successful.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method for this vessel. It is structurally sound, and the geometry is expressed well using 3d printing. Using 3D printing allows for there to be no additional assembly with a design like this, as it is printed with interlocking parts.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, I believe it is successful to an extent. There is a definite gap between each of the planes, as I removed the bar that ran along the top; however, with a defined purpose, i.e. holding apples, the design can be modified to have the exact spacing needed to hold an average sized apple, but that brings up the question that if the function is so specific, does that make the overall product viable? Or is it only viable as an "apple holder," and is there evidence that there is a need for such products on the market.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on continuing to explore the functionality of this product, and redesign it in order to increase the user's ability to use it. I appreciate the angles and geometric shapes being defined; however, I feel there should be additional exploration on the size of the planes or the number of them in order to better the overall functionality.

Product Evaluation Sheet:

Date: Oct 9, 2013

Day/Product #: 13

Cost: $27.44

Volume (cubic centimeters): 152.47

Print Time: 6 hrs and 20 min

Size of Product (inches): X 7.808 Y 7.808 Z 4.060

Ordering Principle of Design: Hierarchy

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 5 iteration, and evolving it based on the ordering principle of design hierarchy. To push this iteration forward from the previous, I explored using the overall lines and angles of the day 5 iteration, but transforming them into planes that intersected in the center. I also removed the perimeter bar along the top. The hierarchy in this iteration is demonstrated in numerous ways. It is represented through the solid and voids of this vessel, as well as, the elements above and below the central axis.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method for this vessel. It is fairly structurally sound, and the simple geometry is expressed well using 3d printing. The 3d printing process is utilized through the interlocking planes that require no additional assembly.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, I believe it is successful to an extent. There is a definite gap between each of the planes as I removed the bar that ran along the top and created additional space between the planes; however, with a defined purpose, i.e. holding apples, the design can be modified to have the exact spacing needed to hold an average sized apple, but that brings up the question that if the function is so specific, does that make the overall product viable? Or is it only viable as an "apple holder," and is there evidence that there is a need for such products on the market. (this is a similar comment from yesterday's iteration.)

Ideas for Redesign:

In terms of ideas for redesign, I would focus on continuing to explore the functionality of this product, and redesign it in order to increase the user's ability to use it. I appreciate the angles and geometric shapes being defined; however, I feel there should be additional exploration on the size of the planes or the number of them in order to better the overall functionality. (Similar to yesterday's iteration's remarks)

Product Evaluation Sheet:

Date: Oct 10, 2013
Day/Product #: 14
Cost: $30.52
Volume (cubic centimeters): 169.56
Print Time: 6 hrs and 20 min
Size of Product (inches): X 7.964 Y 9.772 Z 4.054

Ordering Principle of Design: Rhythm/Repetition

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 7 iteration, and evolving it based on the ordering principle of design repetition/rhythm. To push this iteration forward from the previous, I explored using a solid and void pattern that mimics the Day 7 iteration. The ordering principle of rhythm and repetition is reflected well in the design of this vessel; however, because of the intersection between the two patterned planes, the rhythm gets interrupted along the axis, and is not as successful.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method for this vessel. It is fairly structurally sound, although there is still an element of fragility in the product. I feel 3D printing is a good fabrication method for this product.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, I believe it is successful to an extent. Despite the somewhat fragile structure. The vessel is certainly functional as a container to hold objects larger than the size of the voids. Overall, I would like to have push this design further as I'm dissatisfied with it in its current state.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on the pattern and the connection between the two patterned planes. Whether it is embracing the chaos of the intersection as reflected in the overall design, or changing the overall form/shape to better suit the repetition and rhythm of the pattern, there are numerous ways to approach the next iteration of this vessel.

Product Evaluation Sheet:

Date: Oct 11, 2013

Day/Product #: 15

Cost: $41.30

Volume (cubic centimeters): 229.42

Print Time: 4 hrs and 27 min

Size of Product (inches): X 10.00 Y 7.00 Z 2.058

Ordering Principle of Design: Rhythm/Repetition

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 7 iteration, and evolving it based on the ordering principle of design repetition/rhythm. To push this iteration forward from the previous, I explored using the current repeated pattern, but changing the form to make the rhythm more fluid. Overall, the ordering principle of rhythm and repetition is successful, and is demonstrated well through the design of the vessel.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method for this vessel. It is structurally sound, and as the printing process allows for no additional assembly, these patterned pieces blend together seamlessly. The form, although not complex, utilizes the many advantages of the 3D printing fabrication process.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, I believe it is successful. The form itself allows for various amounts of objects to be placed in the vessel and in a variety of sizes. The lack of voids creates a more versatile vessel, and the design offers a more flexible capacity. Overall, I feel the product is quite viable, and I look forward to further iterations of this design.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on the increasing the complexity of the pattern. I appreciate the pattern (repetition/rhythm) dictating the form of the vessel, and I hope to continue to iterate additional products that push that idea forward, while keeping in mind the successes of this design iteration.

Product Evaluation Sheet:

Date: Oct 16, 2013

Day/Product #: 16

Cost: $17.58

Volume (cubic centimeters): 97.67

Print Time: 4 hrs and 6 min

Size of Product (inches): X 7.979 Y 7.922 Z 2.02

Ordering Principle of Design: Rhythm/Repetition

Evaluation and Reflection (successes and failures):

In this iteration, I am still focusing on my Day 7 iteration, and evolving it based on the ordering principle of design repetition/rhythm. To push this iteration forward from the previous, I explored using same idea as the current repeated pattern, but changing the overall shape/form to create a repeated pattern in both the solid and void aspects of this design. Overall, the ordering principle of rhythm and repetition is successful, and is demonstrated well through the design of the vessel.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method for this vessel. It is structurally sound, and as the printing process allows for no additional assembly, these patterned pieces blend together seamlessly. The form, although not complex, utilizes the many advantages of the 3D printing fabrication process.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, I believe it is fairly successful; however, I would focus on the scale of the vessel in order to make it a more viable product. The current function of the vessel as a container has its limits on the size and amount of objects. Their are numerous aspects of this design that are effective, but potentially in a different type of product. The shadows that are being casted through the individual pieces are interested, and I look forward to the next step of transforming this product from a vessel into a new viable product

Ideas for Redesign:

In terms of ideas for redesign, I would focus on the increasing the complexity of the pattern. I appreciate the pattern (repetition/rhythm) that is formed by both the solid and void aspects of the design, and I hope to keep that aspect in mind as I go on to more iterations. I am also looking forward to transforming this product, and utilizing the design characteristics into a new viable product.

Product Evaluation Sheet:

Date: Oct 17, 2013

Day/Product #: 17

Cost: $16.78

Volume (cubic centimeters): 93.21

Print Time: 2 hrs and 35 min

Size of Product (inches): X 7.838 Y 9.270 Z 1.132

Ordering Principle of Design: Rhythm/Repetition

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 8 iteration, and evolving it based on the ordering principle of design repetition/rhythm. To push this iteration forward from the previous, I explored altering the overall form of the vessel in order to increase the capacity of the vessel. I also wanted to redesign the pattern in order to make it more rhythmic and organized, while still incorporating the hierarchy established in the previous design. Overall, I believe the design is successful in its interpretation of rhythm and repetition as the pattern has both a repetitive nature, and is expressed rhythmically.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method for this vessel. It is fairly structurally sound, and as the printing process allows for no additional assembly, these patterned pieces blend together seamlessly. The complex form utilizes the many advantages of the 3D printing fabrication process.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, I believe it is fairly successful. By changing the form from the previous iteration, it has enabled the capacity of the vessel to increase; however, the use of both solid and voids make the vessel limiting in what it can contain. The overall design and complex pattern illustrated in this design follows my aesthetic as a designer, and I look forward to further iterations of this design.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on utilizing the pattern to help dictate the transformation of the product. The impact of the solid and void aspects to this design should be considered as I push this design forward into the transformation stage.

Product Evaluation Sheet:

Date: Oct 18, 2013

Day/Product #: 18

Cost: $28.44

Volume (cubic centimeters): 157.99

Print Time: 3 hrs and 37 min

Size of Product (inches): X 8.174 Y 9.86 Z 2.175

Ordering Principle of Design: Rhythm/Repetition

Evaluation and Reflection (successes and failures):

In this iteration, I am still focusing on my Day 8 iteration, and evolving it based on the ordering principle of design repetition/rhythm. To push this iteration forward from the previous, I explored altering the overall form of the vessel, while continuing to explore the intersection of the elements. In this design, I wanted to create a more organized repeated pattern, while still having the elements of hierarchy from the previous iteration across the axis. Overall, the use of rhythm and repetition in this design is successful as the pattern is shown both radially, but also from the inside out; however, there was a design error in my modeling that had more elements on one side than the other, which to me detracts from the overall success of the design.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method for this vessel. It is structurally sound, and as the printing process allows for no additional assembly, these patterned pieces blend together seamlessly. The complex form utilizes the many advantages of the 3D printing fabrication process.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, I believe it is fairly successful. By changing the form from the previous iteration, it has enabled the capacity of the vessel to increase; however, the use of both solid and voids make the vessel limiting in what it can contain. The overall design and complex pattern illustrated in this design utilizes solid and voids that casts interesting shadows, which could begin to dictate future iterations of this design as it gets transformed.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on utilizing the pattern to help dictate the transformation of the product. The impact of the solid and void aspects to this design should be considered as I push this design forward into the transformation stage.

Product Evaluation Sheet:

Date: Nov. 5, 2013

Day/Product #: 19

Cost: $13.49

Volume (cubic centimeters): 74.97

Print Time: 3 hrs and 13 min

Size of Product (inches): X 9.7 Y 5.977 Z 1.2

Ordering Principle of Design: Rhythm/Repetition

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 9 iteration, and evolving it based on the ordering principle of design repetition/rhythm. To push this iteration forward from the previous, I explored the scale and form of the vessel, while keeping with the same overall design of the Day 9 iteration. In this design, I wanted to push the previous design further by increasing the overall surface area in order to explore the functionality, while still having the elements of hierarchy from the previous iteration. Overall, the use of rhythm and repetition in this design is successful as the pattern is shown radially, as well as, across a central axis.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method for this vessel. It is structurally sound, and as the printing process allows for no additional assembly, these patterned pieces blend together seamlessly. The complex form utilizes the many advantages of the 3D printing fabrication process; however, I would like to push the complexity of this design further in order to pursue 3D printing as the ideal fabrication method of this vessel.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, I believe it is fairly successful as a vessel. By changing the form form/surface area of the previous iteration, it has enabled the capacity of the vessel to increase; however, the use of both solid and voids make the vessel limiting in what it can contain. The overall design and complex pattern illustrated in this design utilizes solid and voids, which could begin to dictate a new function of this design in the transformation stage.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on utilizing the pattern to help dictate the transformation of the product. The impact of the solid and void aspects to this design should be considered as I push this design forward into the transformation stage. I am also interesting in the formation of layers using this pattern, and how that could begin to change the pattern, form and function, as well as, push the advantages of 3D printing as it's fabrication method.

Product Evaluation Sheet:

Date: Nov. 6, 2013

Day/Product #: 20

Cost: $62.21

Volume (cubic centimeters): 345.60

Print Time: 5 hrs and 46 min

Size of Product (inches): X 7.978 Y 7.978 Z 2.739

Ordering Principle of Design: Rhythm/Repetition

Evaluation and Reflection (successes and failures):

In this iteration, I am still focusing on my Day 9 iteration, and evolving it based on the ordering principle of design repetition/rhythm. To push this iteration forward from the previous, I explored the form of the vessel, as well as, continued the exploration of pattern through the intersection of the elements in the design, but focusing on the intersections across the z axis. In this design, I wanted to push the previous design further by focusing on the complexity of the design, while still having the elements of hierarchy. Overall, the use of rhythm and repetition in this design is successful as the pattern is shown radially, as well as, across a central axis and the z axis.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method for this vessel. It is structurally sound, and as the printing process allows for no additional assembly, these patterned pieces blend together seamlessly. The complex form utilizes the many advantages of the 3D printing fabrication process, and the design would be difficult to fabricate in any other way; however, I would be interested in decreasing the size of the elements in design in order to push the advantages of 3D printing further.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, I believe it is only fairly successful as a vessel. The surface area is limited, and the use of solid and voids limits what the vessel can contain. The design is reversible, and is the same flipped either way, which should help dictate the new function of the design in the transformation stage.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on utilizing the pattern and the reversibility aspect to help dictate the transformation of the product. I would also like to focus on decreasing the size of the individual elements as they seem heavier than they need to be for the design to be successful. The impact of the solid and void aspects to this design should be considered as I push this design forward into the transformation stage. To push the advantages of 3D printing as its fabrication method is important, so I would like to continue the exploration of its complex pattern, but in a more organic, less uniformed shape.

Product Evaluation Sheet:

Date: Nov. 7, 2013

Day/Product #: 21

Cost: $22.12

Volume (cubic centimeters): 122.90

Print Time: 4 hrs and 37 min

Size of Product (inches): X 9.954 Y 6.929 Z 2.138

Ordering Principle of Design: Rhythm/Repetition

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 10 iteration, and evolving it based on the ordering principle of design repetition/rhythm. To push this iteration forward from the previous, I explored the form of the vessel, as well as, investigated how to increase the complexity of the design to make 3D printing a more advantageous fabrication method. In this design, I took the lines from planes of the previous design and continued the exploration of the intersection, by increasing the number of elements and creating a more central intersection as the focal point of the design. Overall, the use of rhythm and repetition in this design is successful as the pattern is shown across a central axis.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing was a successful fabrication method for this vessel. It is structurally sound, and as the printing process allows for no additional assembly, these components come together seamlessly. Although, 3d printing is certainly an efficient method of fabrication for this design, it is arguable that it is the best. The design could be produced in other less expensive methods and materials.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the function, as a vessel, the design is not very functional. The surface area is limited, and the use of solid and voids limits what the vessel can contain. The design focused on intersections, but the space between the solids is too great to hold many objects. In the transformation stage, the new function should utilize what the aspects of this design offers, and I will consider this as I push this design forward.

Ideas for Redesign:

In terms of ideas for redesign, I would focus utilizing the solid and void aspect, as well as, the individual components of this design, as I push the design further into the transformation stage. I would also like to focus on utilizing the advantages of 3D printing as the primary fabrication method for this product, which could include increasing the complexity or integrating any additional parts into the product, i.e. if this were to hang on the wall.

Product Evaluation Sheet:

Date: Nov. 8, 2013

Day/Product #: 22

Cost: $14.16

Volume (cubic centimeters): 78.67

Print Time: 3 hrs and 17 min

Size of Product (inches): X 5.175 Y 5.175 Z 2.12

Ordering Principle of Design: Rhythm/Repetition

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 12 iteration, and evolving it based on the ordering principle of design repetition/rhythm. To push this iteration forward from the previous, I investigated the capabilities of 3D printing as a fabrication method. In this design, I took the lines from the previous design and created thin planes that rotated around a central point in a radial rhythm. Overall, the use of rhythm and repetition in this design is successful as the pattern is shown radially through the planes, as well as, a distinct pattern is created in the joining of the planes in the center.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing could be a successful fabrication method for this vessel; however, the gypsum powder 3D printer does not structurally support how thin this vessel is. The structure is, however, flexible, which is an unusual property of this type of material. This vessel was designed to investigate how thin this printer could print with connected planes, and although, it was successful, the lack of structure makes this product and printing material less viable. The design could also be produced in other less expensive methods and materials.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the viability, the vessel is not structurally sound, so therefore it is not functional. Despite the solid surface area, the scale and proportion are also too small to hold anything of significance. function, as a vessel, the design is not very functional.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on making 3DP a more justifiable method of manufacturing by increasing the size of the elements, as well as, the complexity of the form to ensure that 3DP is the ideal fabrication method. For the sake of this project, I will not be pursuing future iterations.

Product Evaluation Sheet:

Date: Nov. 9, 2013

Day/Product #: 23

Cost: $17.50

Volume (cubic centimeters): 97.23

Print Time: 5 hrs and 23 min

Size of Product (inches): X 7.12 Y 7.12 Z 5.125

Ordering Principle of Design: Rhythm/Repetition

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 13 iteration, and evolving it based on the ordering principle of design repetition/rhythm. To push this iteration forward from the previous, I investigated the capabilities of 3D printing as a fabrication method. In this design, I took the lines from the previous design and created individual pipes that rotated around a central point in a radial rhythm. Overall, the use of rhythm and repetition in this design is successful as the pattern is shown radially, as well as, the hierarchical rhythm from the central point outward is emphasized in the design.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing could be a successful fabrication method for this vessel; however, the gypsum powder 3D printer does not structurally support the unsupported elements in the design. By increasing the thickness of each element, the 3D printer would be a successful fabrication method. One advantage that is emphasized in this design is that no assembly was required, and the central connection point is impactful. Although 3DP is a successful means of fabrication, the design could also be potentially produced in other less expensive methods and materials.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the viability, the vessel had some structural issues that makes the function of this product less viable. Further exploration in design, structure, and form is needed to effectively make this a viable product.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on making 3DP a more justifiable method of manufacturing by increasing the size and connection points of the elements to make it more structurally sound, as well as, the complexity of the form to ensure that 3DP is the ideal fabrication method.

Product Evaluation Sheet:

Date: Nov. 10, 2013

Day/Product #: 24

Cost: $41.47

Volume (cubic centimeters): 230.37

Print Time: 6 hrs and 31 min

Size of Product (inches): X 8.606 Y 4.264 Z 5.00

Ordering Principle of Design: Transformation

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 15 iteration, and evolving it based on the ordering principle of design Transformation. To push this iteration forward from the previous, I investigated how to strengthen the function/concept based on the previous iterations in the design process. The design successfully manipulated the previous iteration into a new functioning form by altering the planes and the space between them to give the product a new function of a desk organizer.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing is a successful method of fabrication for this product. The planes are bent in multiple angles, which would be difficult to achieve with another fabrication method. There was no assembly required for this product, and 3DP would allow a designer or consumer to customize this product to his/her needs. Although, 3DP is successful, other fabrication methods could be used to fabricate a similar item.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the viability, the vessel 's function is successful in that it allows for the consumer to decide how they would want to use the product. The design of this product has allowed for there to be two different ways to organize papers or letters, whether a consumer would want to compartmentalize their documents or place them upright in a central location. The design is also accommodating to be turned upside down as another means of using the product.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on what material I would want this product to be printed out of, and redesign it so that the volume of material is cost efficient to the consumer. There is also the potential for a modular aspect to this design that should be explored further.

Product Evaluation Sheet:

Date: Nov. 11, 2013

Day/Product #: 25

Cost: $17.27

Volume (cubic centimeters): 95.97

Print Time: 5 hrs and 13 min

Size of Product (inches): X 2.460 Y 2.460 Z 7.00

Ordering Principle of Design: Transformation

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 16 iteration, and evolving it based on the ordering principle of design Transformation. To push this iteration forward from the previous, I investigated how to strengthen the function/concept based on the previous iterations in the design process. The new design focused on manipulating the planes of the previous iteration by twisting them as they come together into a new functioning form of a vase.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing is a successful method of fabrication for this product. The planes come together seamlessly and with details that would be difficult to achieve with another fabrication method. There was no assembly required for this product, and 3DP would allow a designer or consumer to customize this product to his/her needs. Although, 3DP is successful, other fabrication methods could be used to fabricate a similar items, but with less detail.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the viability, the vase's function is successful in that it is a closed product that would allow for the holding of water. The design of this vase, although not innovative or new in overall shape as a means to hold flowers, is unique in the details of the form and by its fabrication method. 3DP would allow consumers to decide over size, shape, and details of the design that would be appealing to them.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on what material I would want this product to be printed out of, and redesign it so that the volume of material is cost efficient to the consumer. There is potential for creating a collection based on this vase design that I would be interested in further exploring.

Product Evaluation Sheet:

Date: Nov. 12, 2013
Day/Product #: 26
Cost: $53.03
Volume (cubic centimeters): 294.60
Print Time: 6 hrs and 22 min
Size of Product (inches): X 5.809 Y 5.226 Z 6.718

Ordering Principle of Design: Transformation

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 17 iteration, and evolving it based on the ordering principle of design Transformation. To push this iteration forward from the previous, I investigated how to strengthen the function/concept based on the previous iterations in the design process. An impact of the previous design was the shadows cast through the form, so in the new design I focused on manipulating the elements to change the function to reflect the successes from the previous iteration. The new pendant light was designed with the similar pattern of the previous design, but wrapped in layers to block direct contact with the light source.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing is a successful method of fabrication for this product. The elements of the design are one long strand that gets larger in diameter from the outside in as it undulates and wraps in three layers, giving this design a complexity that could not be created as successfully using other fabrication methods. The fact that no assembly was required is also an important advantage of 3DP this design.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the viability, the pendant light is successful as a vessel of light. The design allows for the casting of intricate shadows; however, it is recommended that a lower wattage bulb be used in the pendant light, as the design is still open enough to allow for part of the light source to be shown.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on what material I would want this product to be printed out of, and redesign it so that the volume of material is cost efficient to the consumer. I would also focus on altering the design, so that no bright spots of the light source could be seen through the pendant.

Product Evaluation Sheet:

Date: Nov. 13, 2013

Day/Product #: 27

Cost: $6.82

Volume (cubic centimeters): 37.89

Print Time: 5 hrs and 6 min

Size of Product (inches): X 5.116 Y 4.627 Z 3.635

Ordering Principle of Design: Transformation

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 18 iteration, and evolving it based on the ordering principle of design Transformation. To push this iteration forward from the previous, I investigated how to strengthen the function/concept based on the previous iterations in the design process. The design investigated the use of solid and voids as a functioning aspect of the new design. The art supply/desk organizer utilizes the voids to create openings for things to be placed in the vessel. Overall the new transformation is successful.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing is a successful method of fabrication for this product. The elements are connected through complex angles and geometry and with no assembly required, and although this could be fabricated using other materials, 3DP is still the ideal method, as the low cost, efficient production time, and detailed precision could not be repeated by hand.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the viability, the desk organizer is successful, as it gives the consumer options of how they would want to use it. There are voids throughout the product in which objects could be placed of various sizes in a more abstract way or the consumer could utilize the larger opening at the top for a more unified approach to desk organization.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on what material I would want this product to be printed out of, and redesign it so that the volume of material is cost efficient to the consumer.

Product Evaluation Sheet:

Date: Nov. 14, 2013
Day/Product #: 28
Cost: $31.83
Volume (cubic centimeters): 176.84
Print Time: 9 hrs and 12 min
Size of Product (inches): X 8.105 Y 5.402 Z 5.125

Ordering Principle of Design: Transformation

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 18 iteration, and evolving it based on the ordering principle of design Transformation. To push this iteration forward from the previous, I investigated how to strengthen the function/concept based on the previous iterations in the design process. The design investigated the use of solid and voids and the shadows that were impactful from the earlier iteration to be used as a functioning aspect of the new design. The pendant light was designed to create a unique light effect inspired by the previous iteration.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing using gypsum powder was not a successful method of fabrication for this product. The outside elements of the design were too unsupported to structurally hold. However, 3DP could be successful using another material. The elements are connected through complex angles and geometry and with no assembly required. The complexity of this design could not be created using another fabrication method.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the viability, the light pendant could not be evaluated due to the fragility of the product, so in this material the function and overall product are not viable.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on what material I would want this product to be printed out of, and redesign it so that it was structurally strong and the volume of material is cost efficient to the consumer.

Product Evaluation Sheet:

Date: Nov. 15, 2013

Day/Product #: 29

Cost: $43.42

Volume (cubic centimeters): 241.23

Print Time: 8 hrs and 28 min

Size of Product (inches): X 6.247 Y 6.225 Z 5.50

Ordering Principle of Design: Transformation

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 19 iteration, and evolving it based on the ordering principle of design Transformation. To push this iteration forward from the previous, I investigated how to strengthen the function/concept based on the previous iterations in the design process. The design investigated the use of solid and voids and the shadows that were impactful from the earlier iteration to be used as a functioning aspect of the new design. The pendant light was designed to continue the pattern from the previous iteration, but by turning the elements into planes in hopes of blocking the light source while creating an effective light/shadow pattern.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing is a successful method of fabrication for this product. The pattern, details, and connections in this design utilize the advantages of 3DP, as well as, the fact that no additional assembly was required.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the viability, the light pendant is successful. The patterned wrapping planes are able to block the light source, while creating a unique light and shadow pattern.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on what material I would want this product to be printed out of, and redesign it so the volume of material is cost efficient to the consumer. Also, I would like to investigate other materials to increase the translucency of the material for a more effective light.

Product Evaluation Sheet:

Date: Nov. 16, 2013

Day/Product #: 30

Cost: $34.26

Volume (cubic centimeters): 190.32

Print Time: 4 hrs and 40 min

Size of Product (inches): X 2.737 Y 2.737 Z 7.671

Ordering Principle of Design: Transformation

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 20 iteration, and evolving it based on the ordering principle of design Transformation. To push this iteration forward from the previous, I investigated how to strengthen the function/concept based on the previous iterations in the design process. The design investigated the use of intersecting patterns that were utilized in the previous iteration. The design focused on how the pattern could transition into a functioning aspect of the design. The vase illustrated the gradual opening and closing of the design to create the bottom half of the vase as a closed element that could hold water.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing is a successful method of fabrication for this product. The pattern, details, and connections in this design utilize the advantages of 3DP, as well as, the fact that no additional assembly was required. The vase design and form could also be customized by the consumer using 3DP as a fabrication method.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the viability, the vase is successful, as it has the ability to hold water to support flowers; however due to the nature of the design only half of the vase can support water, so it would have to be refilled more frequently that an entirely closed vase.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on what material I would want this product to be printed out of, and redesign it so the volume of material is cost efficient to the consumer.

Product Evaluation Sheet:

Date: Nov. 17, 2013

Day/Product #: 31

Cost: $23.76

Volume (cubic centimeters): 131.99

Print Time: 6 hrs and 5 min

Size of Product (inches): X 9.007 Y 4.231 Z 5.197

Ordering Principle of Design: Transformation

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 21 iteration, and evolving it based on the ordering principle of design, Transformation. To push this iteration forward from the previous, I investigated how to strengthen the function/concept based on the previous iterations in the design process. The design investigated the manipulation of the previous form to serve a new function. The previous vessel transformed into a coat hook based on the design of the vessel. The protruding independent elements were digitally manipulated to explore this new function.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing is a successful method of fabrication for this product. As this design needs additional hanging attachments, 3DP allows for that to be built into the design and printed all at once. Also the various angles of the bends of each element would be difficult to reproduce using other fabrication techniques. The angles, details, and connections in this design utilize the advantages of 3DP, as well as, the fact that no additional assembly was required.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

In terms of evaluating the success of the viability, the coat hook is successful; although could be pushed further to accommodate for more than a couple hanging objects. The scale is functional; however, further iterations could be done to investigate a change in scale, proportion, and modularity.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on what material I would want this product to be printed out of, and redesign it so the volume of material is cost efficient to the consumer, as well as, investigate scale proportion, and modularity.

Product Evaluation Sheet:

Date: Nov. 18, 2013

Day/Product #: 32

Cost: $18.12

Volume (cubic centimeters): 100.64

Print Time: 4 hrs and 43 min

Size of Product (inches): X 7.125 Y 7.125 Z 2.671

Ordering Principle of Design: Transformation

Evaluation and Reflection (successes and failures):

In this iteration, I am focusing on my Day 22 iteration, and evolving it based on the ordering principle of design, Transformation. To push this iteration forward from the previous, I investigated how to strengthen the function/concept based on the previous iterations in the design process. The design investigated how to strengthen the previous form to better the function. The vessel focused on strengthening the structure and form to continue the function of a vessel.

3D Printing Role:

Evaluation and Reflection (successes and failures):

Overall, 3D printing is a successful method of fabrication for this product. The design's complex form utilizes the advantages of 3DP. The connections and intersections would be difficult to produce using other fabrication techniques. The angles, details, and connections in this design utilize the fact that no additional assembly was required using 3DP.

Overall Viability as a Product:

Evaluation and Reflection (successes and failures):

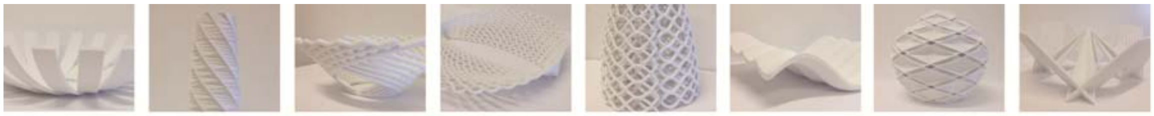
In terms of evaluating the success of the viability, the vessel is successful; although could be pushed further in scale and proportion. The scale is functional; however, further iterations could be done to investigate future options of the design.

Ideas for Redesign:

In terms of ideas for redesign, I would focus on what material I would want this product to be printed out of, and redesign it so the volume of material is cost efficient to the consumer, as well as, investigate scale and proportion.

APPENDIX B

3DP GUIDELINES



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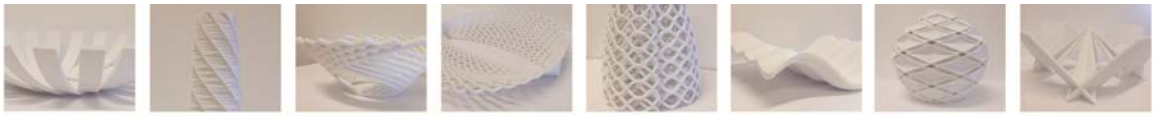
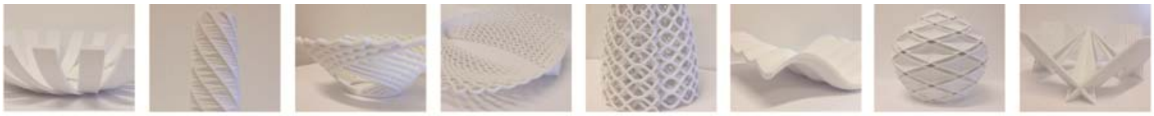


Introduction:

The intent of this set of guidelines is to provide designers and individuals a succinct primer on 3D Printing. The guidelines give the designer an overall understanding of what 3D printing is, as well as, how and when it can be incorporated into the design process or used as the final fabrication method. Current advantages and disadvantages of the fabrication method will be identified to help designers be able to make decisions on its suitability in their design process or as a final manufacturing method. The guidelines also provide the basics on how to prepare a digital model for 3D printing, what types of materials to consider for 3D printing, and how to access a 3D printer.

What is 3D Printing:

3D printing is an additive manufacturing process that builds 3D objects layer by layer from a digital model. After a 3D digital model is modeled in 3D software, the file is exported to an appropriate file type such as a STL (stereolithography) file, which can be read by a 3D printer. The 3D printer then interprets the file by creating virtual cross sections of the model and begins building up the object starting from the bottom layer with layers being as thin as 0.0006 inches. Depending on the material, the 3D print head either squirts out or solidifies powder, molten, or liquid material onto the bed in a specified flat pattern based on the model (Barnatt, 2013). Either the print head or the print bed moves on the Z-axis to allow for the next thin layer to be added. Each layer solidifies before the next thin layer of the object is printed. These steps repeat to eventually build a 3D object comprised of multiple thin layers (Kurman and Lispon, 2013).



3D Printing Applications:

3D Printing is an advancing technology that can allow users to design, fabricate, and market their products, and through the Internet, the technology is becoming more available to individuals. The digital desktop tool allows designers to make physical objects in shapes and forms that have never before been possible, opening doors to a world of new possibilities in not only design and fabrication, but also in the way products can be distributed (Kurman & Lipson, 2012). There are many industries that are benefiting from 3D printing technologies including architecture, automotive, aviation, education, fashion, industrial, manufacturing, medical, and product design (Winnan, 2013). In product design, 3D printing can be used for building concept models and functional prototypes, creating molds for casting, doing market research, and fabricating finished goods.








Advantages of 3D Printing:

--Acceleraes the Design Process: As a prototyping tool, designers can utilize 3DP as a means to rapid prototype. 3D Printing (3DP) can fabricate physical models faster and more efficiently than other manufacturing processes, in order for a designer to assess, evaluate, test, and make accurate decisions on the success of a product as early as the conceptual design phase. Faster-turnaround allows designers to make adjustments throughout the design process without lengthening it (Lipson & Kurman, 2012).

--Cost Effective: For companies, the ability to refine form, fit, and function in product development through 3DP can improve production costs and time to market. For individuals, designers, and students, 3DP has leveled the playing field as they can enter the same market with less financial risk (Dimitrov, Schreve, Beer, 2006). Designers are able to use companies such as Shapeways or i.Materialise as a platform to sell and print their designs without the added initial costs of a typical start-up.

--Moveable Parts and No Assembly Required: 3DP allows for fully functional moveable or interlocking parts to be printed without the need for further assembly. Through 3DP, connections and joinery are done for you (Berman, 2012). It is important to note that some assembly may be required if a print is larger than the bed size, as printing a product in parts to then reassemble is an option.

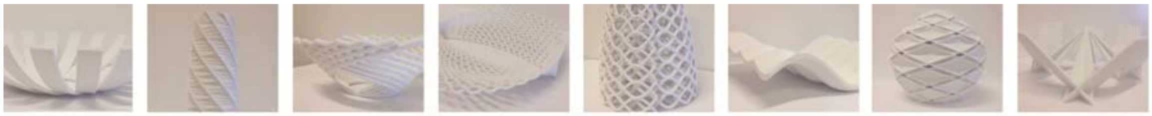
--Mass-Customization: With 3DP, no single product has to be the same, which makes one of its biggest advantages its ability to customize products. A single 3D printer does not need to be re-tooled with every print, just a new digital file and a fresh batch of the raw material is needed (Lipson & Kurman, 2012).

--Environmentally Friendly: 3DP is an additive manufacturing process that uses only the required amount of raw material to make the product than is needed, which leads to very little material waste (Anderson, 2012). Some printers may add structural supports during the print process, but these can be removed post print.

--Complex Geometries: 3DP is enabling designers to fabricate products that cannot be produced using traditional manufacturing methods. In addition 3DP a complex shape does not necessarily cost more than printing a simple shape. Complicated forms do not require more time, skill, or cost than a simpler design (Lipson & Kurman, 2012).

--Control of the Manufacturing Process: 3DP allows designers to be more involved in the manufacturing process rather than having a product be manufactured in a factory (Lipson & Kurman, 2012). Designers are also able to design and fabricate products with a high level of detail and precision.

--Breaks Barriers between Designers and Materials: 3DP allows for designers to work in a variety of new materials, such as ceramics, metals, and plastics without having to be trained in the specifics of material fabrication (Lipson & Kurman, 2012).



Disadvantages of 3D Printing

--Initial Cost: 3DP can be an expensive means to fabricate a prototype or finished good, especially for students. As cost is based on quantity of material used, understanding how to produce a more cost-effective digital model (explained further in the Preparing a Model section of these guidelines) can help designers make informed decisions on whether 3DP is an effective and economical means of fabrication for their needs. However, this potential disadvantage could also be an advantage for industrial design/product companies as 3DP could be a cost effective way to avoid traditional costly molds and expensive labor.

--Limited Print Bed Size: Most 3D printing machines are small enough to fit on a desktop, which means that their build chamber size is proportional to that. There are industrial 3D printers that can create larger parts or products; however, these are much more expensive. Designers can also overcome this restriction by dividing a product into multiple parts to print separately. Pieces can then be glued or connected back together after each piece is printed (explained further in the Preparing a Model section of these guidelines). Also, it is important to note that multiple products can be printed at once as long as they all fit in the printer bed.

--Usability: As 3DP relies on reading a digital file, an important element of using 3DP in the design process is the ability for the designer to know 3D modeling software, and be able to design well in it.

--Material Limitations: Currently, 3DP can print in such materials as plastics, resins, some metals, and ceramics. The mixing of materials is still under development; however, as technology increases the number of printable materials will increase.

--No Economy of Scale: Despite the fact that this can be seen as an advantage because of 3DP's ability to customize, there is no volume discount as each price is for a per unit basis. There is no cost savings between printing the first product and printing the thousandth (Anderson, 2012).







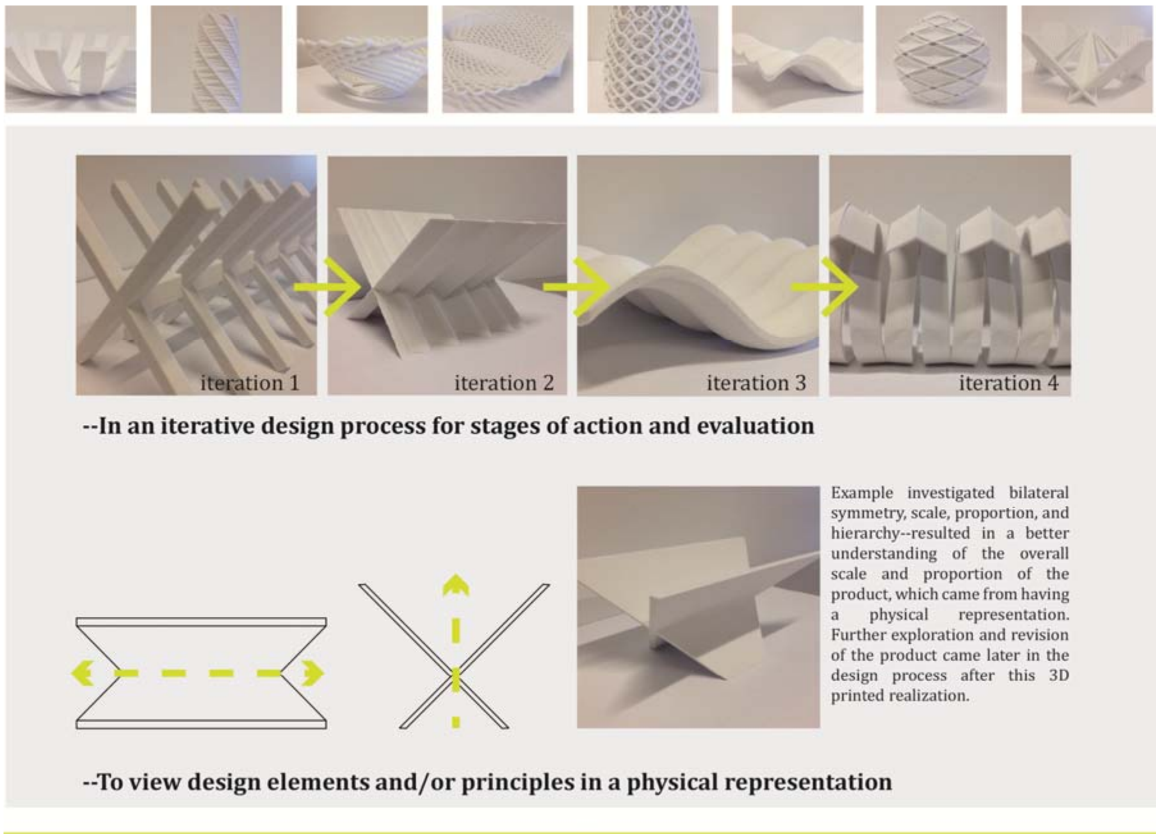

3D Printing in the Design Process:

Incorporating physical modeling into the design process is not a new concept in product or architectural design. The creation of representational models allows designers to realize their mental concept, and can lead to new forms beyond the initial concept. 3DP allows for prototypes to not only be developed faster, but also can lead to new inspirations, design ideas, or fabrication techniques that through other methods may not have been realized (Sass & Oxman, 2006). After understanding the advantages and disadvantages, designers can begin to focus on when to incorporate 3DP into their design process, which will enable them to use 3DP effectively and efficiently throughout their process.

When to Use 3DP:

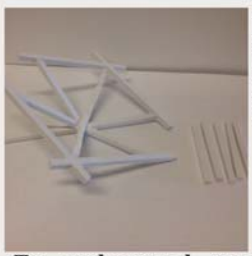

These scaled ideation models were printed to illustrate various concepts and ideas. Some were modular units to test, and others were expressive of a potential overall form. Having these models allowed us to try different variations, as well as, get ideas for further product development.

--As a ideation concept modeler for early ideation stages of design


iteration 1
iteration 2
iteration 3
iteration 4
--In an iterative design process for stages of action and evaluation
Example investigated bilateral symmetry, scale, proportion, and hierarchy--resulted in a better understanding of the overall scale and proportion of the product, which came from having a physical representation. Further exploration and revision of the product came later in the design process after this 3D printed realization.
--To view design elements and/or principles in a physical representation

Designed by Proxy Design Studio, "Mechaneu v1" is a kinetic 3D printed series that explores 3D printing as a complex art form. The sculpture features a network of 64 interlocking gears that if one gear is spun then the entire sphere is catalyzed with rotation.

--To investigate complex form studies



In this example, the product displayed had constructional issues that were revealed after printing.

--To understand material - constructional aspects of a product

These images display various materials and thicknesses of similar products, which were being tested to understand the structural and physical behavior of each.

--To understand structural and physical behavior of a product or part.

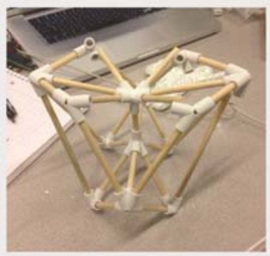







*The print time of a product is proportional to the size and complexity of the object. A product like a cellphone case takes about 2 hours to print on average.

--To test multiple versions of the same product quickly—rapid prototyping*

First image tests 3D printed gears for their fit and function. Second image is a scaled model with 3D printed connectors which determined a need for changing the shape of the top connectors for a lack of fit.

--To test parts of a product—fit, form, function

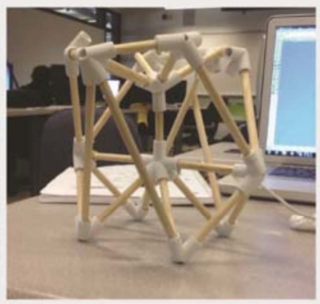






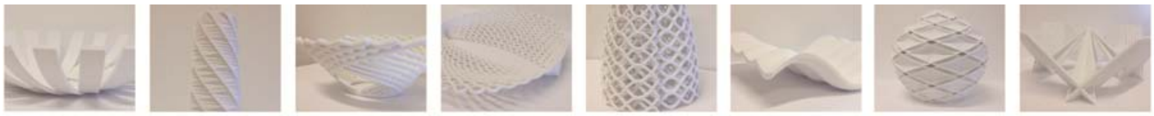

LEGO is using 3D printing in the design stage of their products by producing work that users can interact with before it reaches the market. This 3D printed car was showcased at the 2012 LEGO World in Copenhagen.

--To incorporate user-centered design process strategies—users can interact with physical object

In this example, 3D printed connectors were printed to put together a scaled model of a stool. The final product would be created from both 3D printed connectors (in a different material) and wooden dowels.

--As a scaled modeler to create scaled prototypes or parts of a prototype



These pendant light prototypes were 3D printed using a zcorp printer and are fully functional light prototypes.

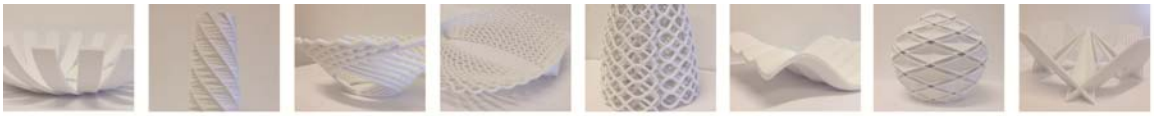
--As a fully functional prototype—product design

This scaled model of a bridge is not only a presentation visualization tool, but also assists in understanding the structural details of the bridge.

--As a presentation visualization tool—architectural scaled model

3D Printing for Finished Products

3D printing is currently being used in the fabrication of finished goods because of the advancement of the technology and the wide range of printable materials. When utilizing a 3D printer in order to fabricate a final product, it is important to have first tested the printability of the product in the desired material. This can be done in multiple ways such as actually test printing an object, using a software such as Netfabb Studio Basic, which can analyze, edit, and repair meshes in models, or by using a company such as Shapeways as they offer analysis of a model after uploading, which will tell you which materials your model can be printed in based on the overall size and wall thicknesses. It is also important to have answered questions regarding the product you want to produce such as: Does 3D printing make sense? How many products will I be producing? Do I want this to be mass-produced? Who is the consumer? How do I want to market the product? Is customization important? What type of initial funding do I have? Understanding the importance of the answers to these questions will help inform the designer if 3D printing as a final fabrication method is right.



When to Use 3DP:

--After conducting a cost-benefit analysis on using 3DP versus other possible fabrication methods.

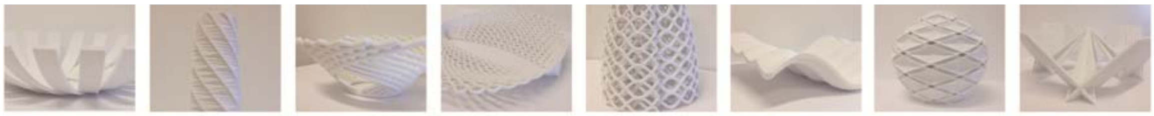
--When a designer wants to focus on customizing products for each customer. As 3D printing offers no economy of sale, mass-customization is a significant reason to utilize 3D printing as a final fabrication method.

--If the product or part include complex geometries that cannot be fabricated using any other manufacturing method, which is one of the biggest advantages of 3D printing.

--After understanding and test printing the various materials available that would be appropriate for the product. Testing the strength of a material and the printability of an object are important.

--When utilizing a third party 3DP sharing platform to enter the product onto the market for consumers to purchase. Companies such as Shapeways and i.Materialise are enabling designers to upload their products for others to purchase and have 3D printed.

--When a designer wants to experiment with a variety of materials with no additional training. A product can be printed with ease in a variety of materials, such as plastics, metals, and ceramics.



Each of these products was designed to use 3D printing as a final fabrication method, and they are available through Shapeways to have printed. The necklace and light are printed in a SLS nylon plastic and the vase is printed in ceramic.







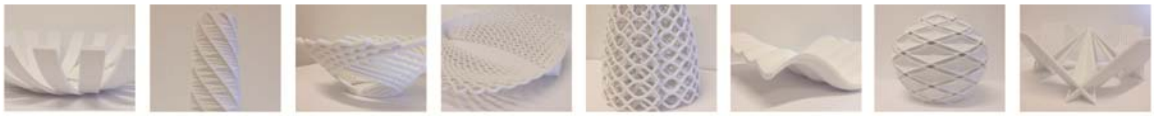

Using a 3D Printer:

In order to utilize 3D printing in the design process or as a final fabrication method, it is important to understand the various software available, the steps to creating a printable model, and how to find access to a 3D printer. It is also important to note that this section of the guidelines is not meant as an operational guide to a 3D printer, but as a guide to help designers prepare a file to then be 3D printed. Currently most individuals and/or designers do not own 3D printers, and will not be using a 3D printer directly by themselves, but rather going through 3rd party printing services or having the assistance of a local professional.

Computer-Aided Design (CAD) Software*:

--Rhinoceros: www.rhino3d.com
--Google Sketchup (free): www.sketchup.com
--Art of Illusion (free): www.artofillusion.org
--Blender (free): www.blender.org
--3DCrafter (free): www.amabilis.com
--3DS Max: http://www.autodesk.com/products/autodesk-3ds-max/overview
--AutoCAD: http://www.autodesk.com/products/autodesk-autocad/overview
--Solidworks: www.solidworks.com

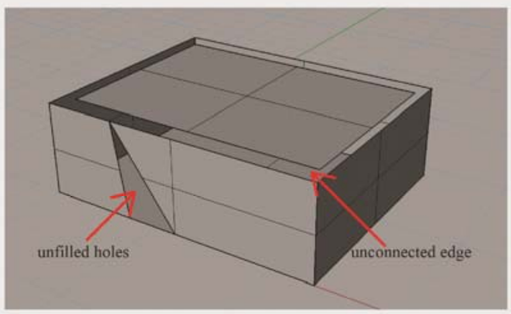
*Note: 3DP is not limited to these software products

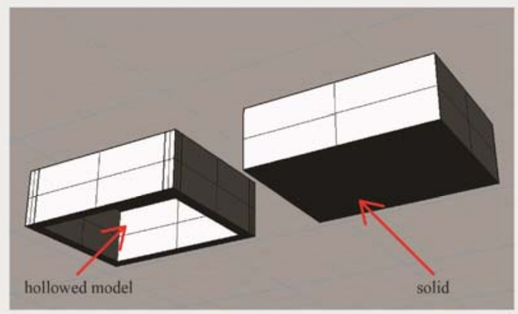


Preparing a Model for 3D Printing:

1. Objects must be closed or watertight. Be sure to check for any unfilled holes, unconnected edges or floating objects in the digital model. An unfilled hole or unconnected edge can cause errors in the printing process as well as floating objects will print disconnected from the model.

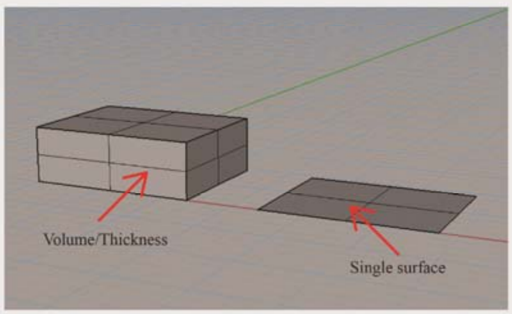
2. Large objects should be hollow, which reduces waste of material, and lowers the cost printing. Identify wall thickness restrictions for the desired material in order to model the appropriate thickness while maintaining model strength. If a model is hollow and does not have an open side, a discrete hole should be designed into the model in order to release the excess powder post printing.

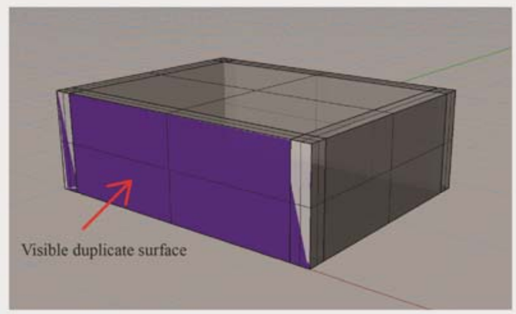


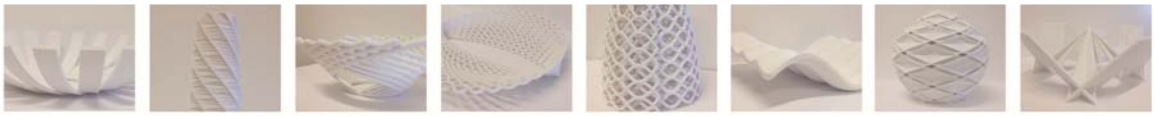


3. Objects must contain volume and not have only single surfaces. All surfaces must have a specified thickness in order to print. Please see Table 1 on pages 23-24, which identifies minimum thicknesses per material.

4. Eliminate all duplicate surfaces. Identical surfaces in models, which exist one on top of the other must be deleted as they can cause errors in the printing process. Most CAD software has a tool to locate duplicate objects, and some will show a duplicate surface as flickering in the working model.

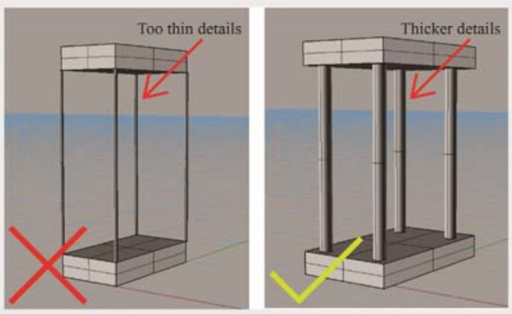


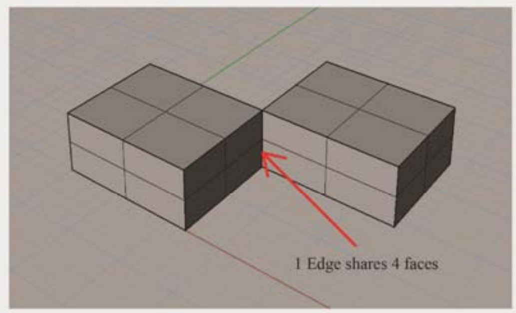


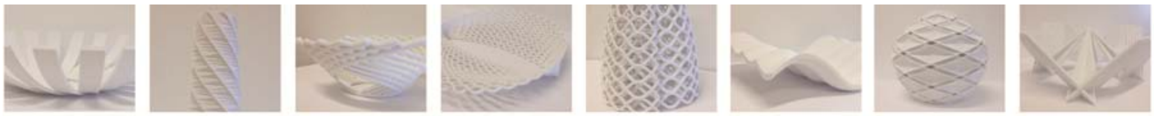


5. Thicken supported or unsupported details based on desired print material minimum thickness to ensure they do not break post-printing. Please refer to Table 1 on pages 23-24 for appropriate material thicknesses.

6. Eliminate non-manifold geometry, which is any edge shared by more than two faces.

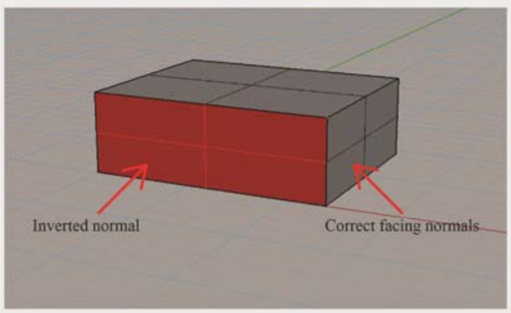


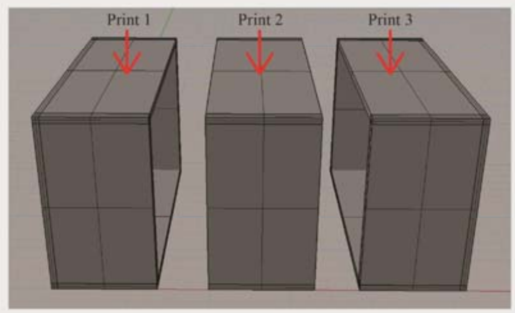




7. Correct surface normals. As surfaces have two sides, surfaces should have their normals pointing in the correct direction. Surfaces in CAD models have an inside and outside face, and having a surface face on the wrong side can affect the overall readability of the model as the 3D printer doesn't comprehend where to place the material.

8. Understand the 3D printer's print bed constraints and for larger objects split the model into sections to print one-by-one to then join together both pieces post-printing.












9. To print a scaled model of an object, the object should be modeled at the desired scale in order to ensure proper printing thicknesses. Only scaling down from a larger model to a smaller one can cause walls and/or details to be too thin to print properly.

10. Convert/Export file to an .STL (stereolithography) or other readable file type. The example below shows how to export a file using Rhino3D.

Other file types: .DAE, .OBJ, .X3D, .X3DB, .X3DV, .WRL

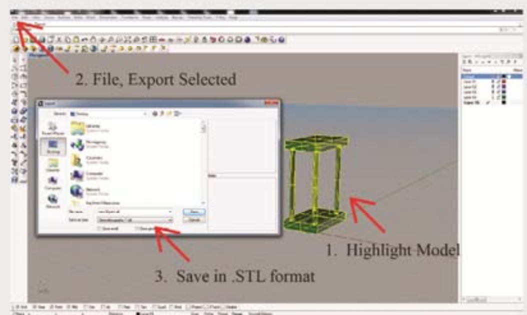


Table 1:

This table displays a variety of the materials commonly available to be 3D printed. It is not a full list as more materials are becoming available. Along with the properties of each material, the most important thing to consider when modeling an object to print is the minimum thickness for each material. The minimum thicknesses can vary slightly depending on whether the detail of the object is supported or unsupported, but the table lists the general rule for each material.

Material	Production Method	Properties	Minimum Thickness
Plastic Nylon	Selective Laser Sintered (SLS)	Polished or rough flexible; colors available	0.7 mm
Alumide	Selective Laser Sintered (SLS)	Grey w/ metallic specks of aluminum. Stiff + brittle	0.7 mm
ABS plastic (Acrylonitrile Butadiene Styrene)	Fused Deposition Modeling (FDM)	hard and strong; colors available	1.0 mm
Frosted Plastic	Multijet Modeling (MJM)	Smooth, Brittle, Transparent	0.5 mm
Steel	Metal 3D Printing	Strong, glossy stainless, bronze, gold, nickel, black	3.0 mm
Sterling Silver	3D Wax Printing + Casting	Polished or raw, smooth, strong	0.6 mm








Table 1 continued:

Material	Production Method	Properties	Minimum Thickness
Brass	3D Wax Printing + Casting	High shine; strong, smooth	0.6 - 0.8 mm
Bronze	3D Wax Printing + Casting	Strong, Smooth, highly detailed	0.6 - 0.8 mm
Ceramics	Ceramics 3D Printing + Glazing	Shiny, brittle; colors available	3.0 mm
Full Color Sandstone	Zcorp	Vibrant colors, rough feel, brittle	2.0 mm
Gypsum Powder	Zcorp	brittle, detailed; colors available	4.0 mm
Rubber-like	Selective Laser Sintered (SLS)	highly flexible, durable, black	1.0 mm

Finding a 3D Printer:

As 3D printing is becoming more popular, it is also becoming more available. Many universities are investing in 3D printers with access for students, as it is seen as having important implications for research advancements. Along with schools with design programs, university libraries have begun to play an important role in creating these makerspaces for students. Students have an advantage of gaining first hand access to 3D printing technology; however, finding a printer or using a 3D printing service has never been easier.

3D Printing Services

--Shapeways: A 3D printing marketplace and online printing service based in New York, where individuals can buy, sell, and make their own products. Web Address: www.shapeways.com

--i.Materialise: An online 3D printing service, where designers can create, share, and sell their designs based in Belgium. Web Address: www.i.materialise.com

--Ponoko: Launched as a Personal Factory to make downloadable products in New Zealand that offers online laser-cutting, 3D printing, and CNC routing services. Web Address: www.ponoko.com

--Freedom of Creation: A product design company that specialized in creating and commercializing 3D printed products. Web Address: www.freedomofcreation.com

--RedEye On Demand: A rapid prototyping service bureau for industries. Web Address: www.redeyeondemand.com

--Moddler: A 3D printing and 3D scanning company based in San Francisco. Web Address: www.moddler.com

--Thingiverse: A company that has digital designs for physical objects ready to be downloaded and printed. Web Address: www.thingverse.com/

--3D Hubs: A resource for finding local 3D printing services and 3D printers. Web Address: www.3dhubs.com








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Image 1 page 3: http://shop.felixprinters.com/learn
Image 2 page 4: Interior Product Design: Espresso cup in 3D printed ceramic, http://on3dprinting.com/2012/07/14/3d-printed-rocket-fuel-espresso-cup-goes-viral-boosts-sales/
Image 3 page 4: Fashion: 3D printed shoes in SLS plastic, photo credit: http://boingboing.net/2012/03/29/3d-printed-shoes-2.html
Image 4 page 4: 3D printed titanium jawbone, photo credit: http://www.pcmag.com/article2/0,2817,2399887,00.asp
Image 5 page 10: Kinetic Gear Sphere, http://www.beautifullife.info/art-works/3d-printed-spherical-gear-system-kinetic-sculpture/
Image 6 page 11: Cell Phone Rapit prototype, http://www.solidconcepts.com/rapid-prototyping/
Image 7 page 11: 3D print Gear, http://airwolf3d.com/blog/2012/05/08/herringbone-gears/
Image 8 page 12: Lego Car, http://blog.stratasys.com/2012/02/16/lego-turns-design-concepts-into-working-prototypes-using-objet-3d-printer/
Image 9 page 13: 3D print Bridge, http://www.shapeways.com/blog/archives/2165-3d-printing-architectural-maquettes,-models-and-miniatures.html
Image 10 page 16: 3D print necklace, http://www.shapeways.com/model/218209/stereodiamond-necklace.html?li=curatedproductGroup&materialId=25
Image 11 page 16: Origami Vase, http://www.shapeways.com/model/679493/origami-vase.html?li=search-results&materialId=90
Image 12 page 16: Hyphae Lamp, http://n-e-r-v-o-u-s.com/shop/generativeProduct.php?code=99

APPENDIX C

EVALUATION QUESTIONAIRE FROM PHASE III

Project Title: Printable Products: Investigating Three-Dimensional Printing in the Design Process of Interior Products

Group1: Received Guidelines and 3D Printing Demonstration
Group 2: Received Guidelines
Group 3: Received 3D Printing Demonstration

Group #: ________________ Name: _______________________________________

Date: ____________________

Presentation # (circle answer): 1 2

Product: ____

1. Design Concept:
   Describe concept:

   Rank Clarity: (5 being the clearest, 1 being unclear—circle answer)

   1 2 3 4 5

2. Visual Design (models):
   Describe models, explaining details presented:

Rank Models: (5 being the clearest, 1 being unclear—circle answer)

1 2 3 4 5

3. Successes and Failures of Fabrication:
   Explain benefits and/or drawbacks of 3D Printing:

   How did 3D printing affect the design process?

   Do you think 3D printing was the best fabrication method? Why or why not?

   Rank 3D printing: (5 being the most successful, 1 being least—circle answer)

   1 2 3 4 5

4. Additional comments and/or suggestions, successes and/or failures?

GROUPS 1 and 2:

5. Successes and Failures of Guidelines:

How were the guidelines used in this stage of the design process? If so, explain benefits and/or drawbacks:

Rank Guidelines: (5 being very useful, 1 being not—circle answer)

1 2 3 4 5

6. Suggestions for Guidelines:

What changes should be made?

GROUPS 1 and 3:
7. 3D Printing Demonstration:

How did the demonstration affect your use of the 3D printer in this stage of the design process?

Rank Demonstration: (5 being very useful, 1 being not—circle answer)

1 2 3 4 5

APPENDIX D

BODY OF WORK

Figure 58. 3D Printed Lights. Spring 2013

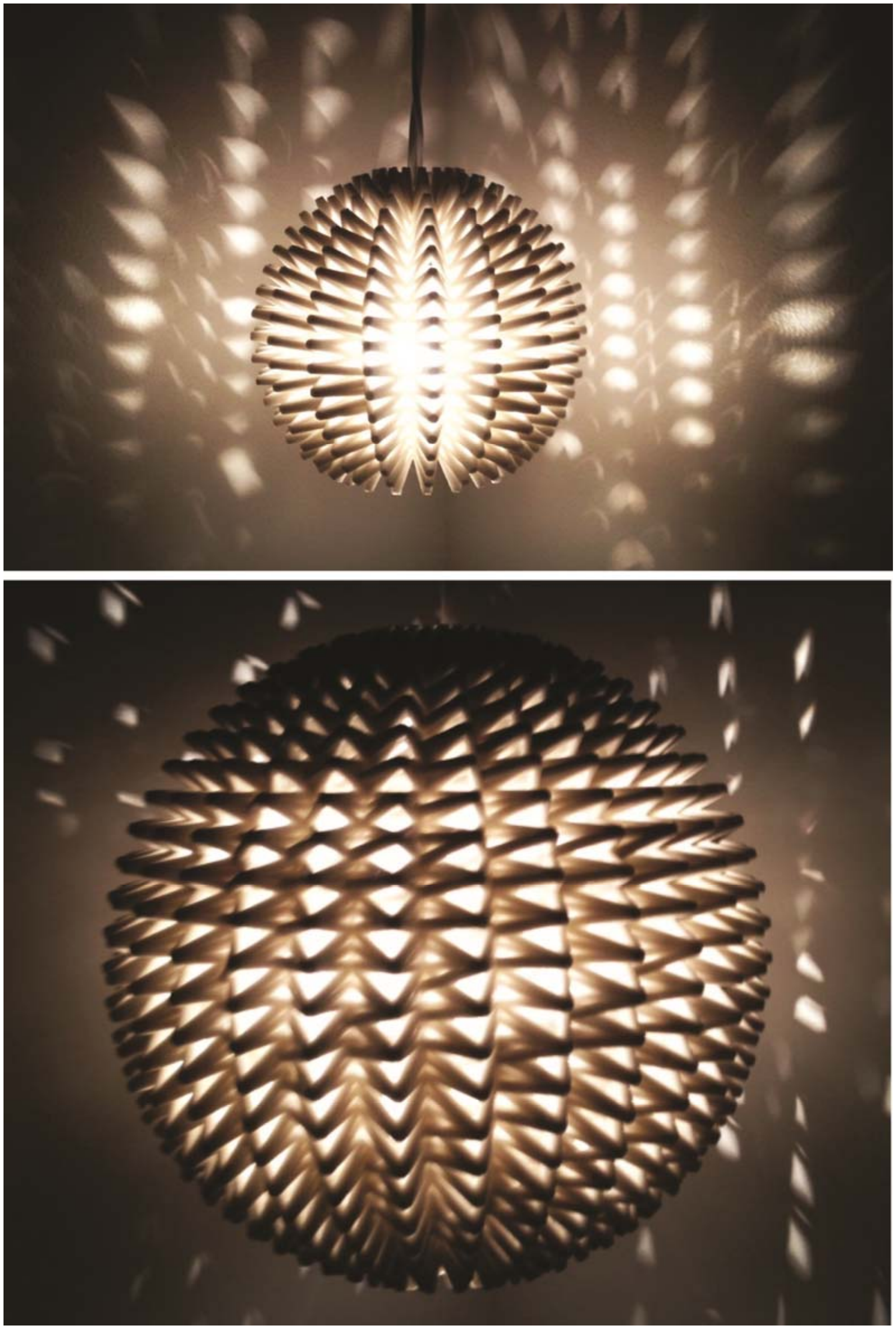

Figure 59. 3D Printed Lights. Spring 2013

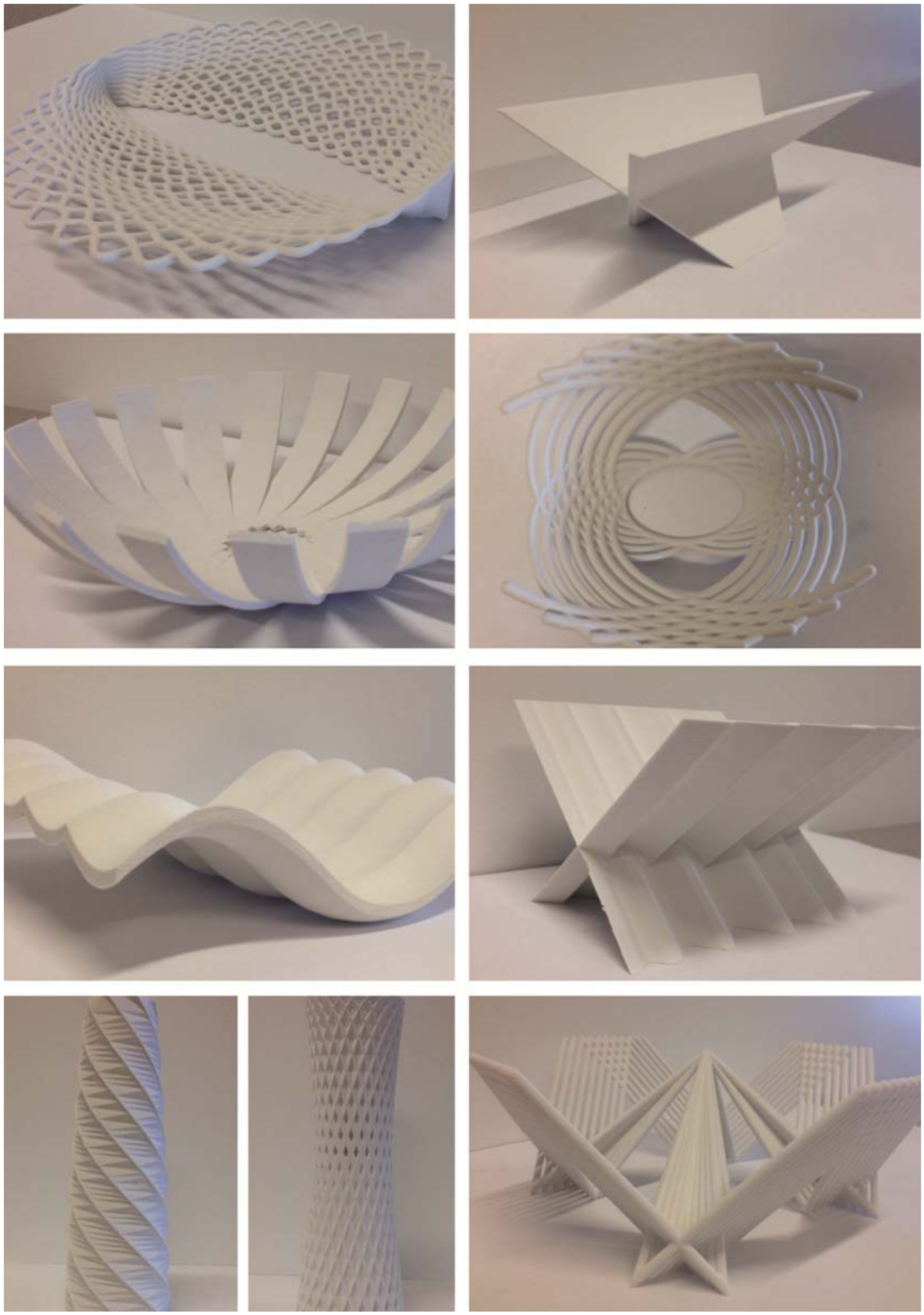

Figure 60. 3D Printed Vessels. Fall 2013

Figure 61. 3D Printed Lights. Fall 2013

Figure 62. 3D Printed Raw Silver Ring. Spring 2014

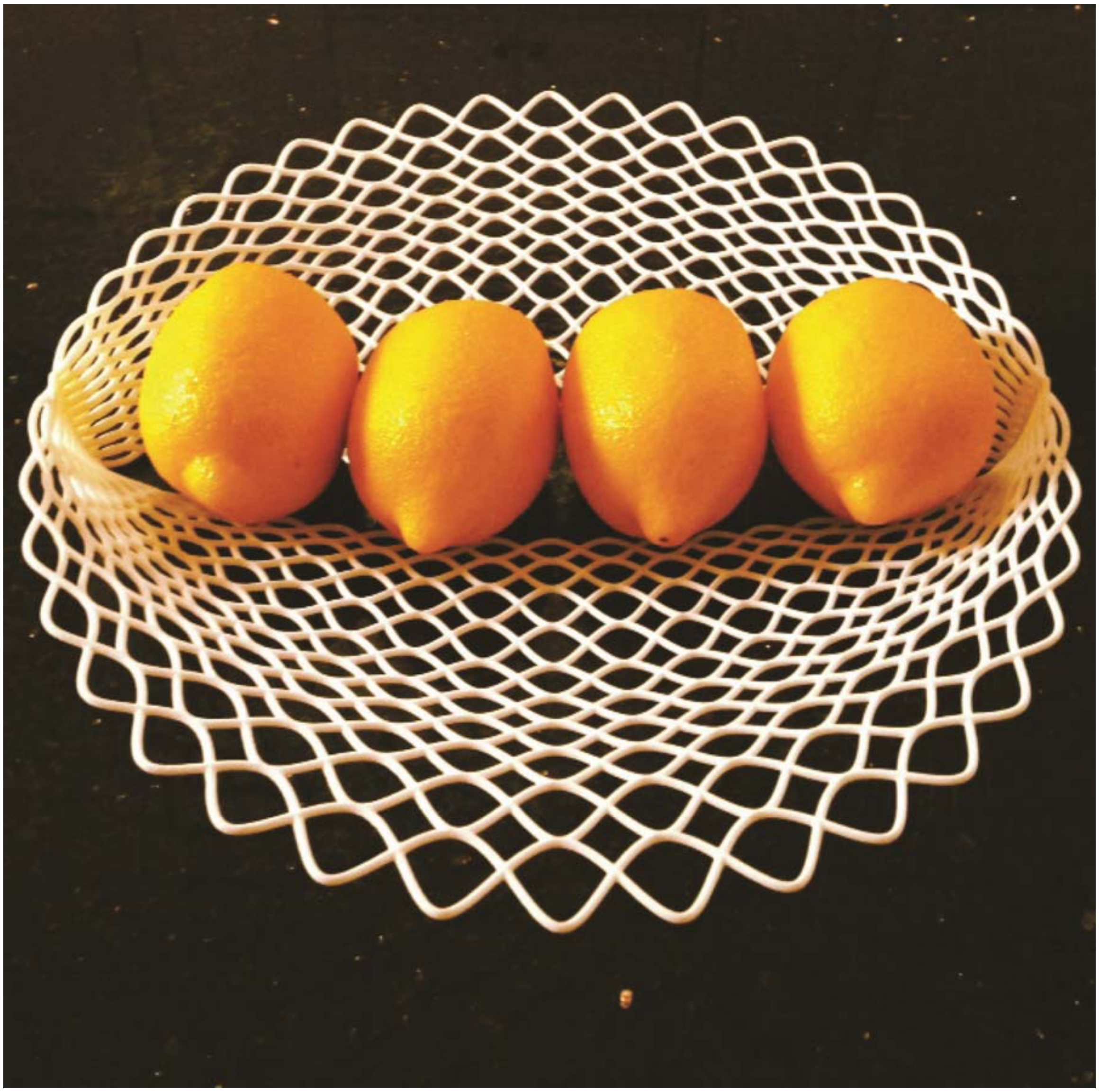

Figure 63. 3D Printed SLS Nylon Vessel. Spring 2014

Figure 64. 3D Printed Ceramic Vase. Spring 2014