A STUDY OF FABRICATION METHODS AND DESIGN OUTCOME ON STUDENT PERSPECTIVE IN AN ACADEMIC INDUSTRIAL DESIGN STUDIO

A Thesis
Presented to
The Academic Faculty

by

Linye Zhang

In Partial Fulfillment
of the Requirements for the Degree
Master of Industrial Design in the
School of Industrial Design

Georgia Institute of Technology
August 2015

A STUDY OF FABRICATION METHODS AND DESIGN OUTCOME ON STUDENT PERSPECTIVE IN AN ACADEMIC INDUSTRIAL DESIGN STUDIO

Approved by:

Dr. Young Mi Choi, Advisor
School of Industrial Design
Georgia Institute of Technology

Kevin D. Shankwiler
School of Industrial Design
Georgia Institute of Technology

Wendell Wilson
School of Industrial Design
Georgia Institute of Technology

Date Approved: May 08, 2015

ACKNOWLEDGEMENTS

I would like to express my special appreciation and thanks to my advisor Dr. Young Mi Choi, you have been a tremendous mentor for me. I became your student for three years. During these years you encouraged my research and allowed me to grow as a great industrial designer. Your advice on both research as well as on my life have been priceless. I would also like to thank my committee members, Kevin D. Shankwiler and Wendell Wilson for serving as my committee members. I also want to thank you for letting my defense be an enjoyable moment, and for your brilliant comments and suggestions, thanks to you.

I wish to express my sincere thank you to my parents, Mr. Jian Zhang and Ms. Hua Wu, who have supported me to accomplish my master degree. You have been concerned about me day and night from afar. You have given me love and encouragement, when I was depressed. Thousands of words welled up in my heart, but no words can express how grateful I am to my parents. The only thing I have to say is I love you so much and forever.

I am especially grateful to Troy J. Whyte, academic advisor, in the department of industrial design. Your always gave me timely, carefully and kindly help, when I have any problems. I would also like to thank the twenty participants and those forty evaluators. All of you have been there to support me when I collected data for my master thesis.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

NPD	New Product Design
CNC	Computer Numerical Control
RP	Rapid Prototyping
SLA	Stereo Lithography
SLS	Selective Laser Sintering
FDM	Fused-deposition Modeling
3D	Three Dimensional
VM	Vacuum Molding
RIM	Reference Information Model
UV	U and V Means the axes of a plane
A	A means average
N	N means the number of terms
S	S means the sum of the numbers being averaged

SUMMARY

The construction of models is an important component in the innovation and final production phase of a design project. They are the key to testing a concept to identify and correct design or usability problems. Models at each stage of the design process should accurately represent the concept and so it is important to choose fabrication methods that are appropriate for the goals of the model. The focus of this paper is to examine the relationship between the fabrication methods used for model construction during the design process and the perceived success of the final design outcome. Sixty industrial design students, both undergraduate and graduate, were surveyed about the methods used to fabricate models during the early conceptual stage and the late testing phase of an assigned design project. Their comments regarding the purpose for choosing each method and the level of contribution to the final design outcome were collected. Results from the survey are presented and potential steps for guiding students to utilize the most effective fabrication method for the design scenario are discussed.

CHAPTER 1

INTRODUCTION

For industrial design, almost no products can come into being without any prototypes or models. New designs are always accompanied with unforeseen problems, because people can never know in advance the design issues and challenges before the idea is actually put into practice [1]. Therefore, it is necessary to create prototypes or models to test whether the new design would actually perform as anticipated or if there will be problems [2]. More specifically, making prototypes or models in the design process can help designers make adjustments to the design, in terms of materials, size, shape, assembly, color, manufacturability and strength [3].

As product design is an iterative creative process linking design and fabrication processes [9], designers will generally make more than one model in the design process. It is recognized by most researchers that designers need to make models in three stages [4-7]. The first stage is evolutionary stage, which helps designers clarify the user requirements. The second stage is called as the experimental stage. Models are built and evaluated iteratively at this stage. In the last stage, exploratory models are made to modify the existing products [6, 8].

With the advancement of technology, fabrication has greatly developed. From traditional handmade model making to digital fabrication, various fabrication methods have been invented, which provide designers a tremendous amount of choice in the model making process appropriate for the stage of development. However, more choices for designers also mean that they may have a better or best choice in different stages and for different products. This range of options poses several questions: Will using an inappropriate fabrication technique lead to poor results? Is faster better? How does one choose the optimum fabrication method for a specific situation?

This study aims to find out the relationship between fabrication methods and design outcomes, involving the influence of the fabrication methods on design outcomes, the effects that designers can obtain with different fabrication methods, and methodologies to select an appropriate fabrication method.

CHAPTER 2

BACKGROUND

2.1 Design Process

New Product design (NPD) refers a process of creating a brand new product [16]. As a matter of fact, this innovative process is not simple, as countless days of research, analysis, design studies, engineering and prototyping, testing, modifying and re-testing are involved until the final design has been perfected [15]. Furthermore, there are many focuses on different aspects and various product design processes. Although the design process is complicated, there are many people who sum it up to a simple pattern.

Jones (1984) defined a pattern in an early example, suggesting a basic structure to the design process of analysis-synthesis-evaluation. The evaluation stage, also the longest stage, involves building models to evaluate the design. A more detailed prescriptive pattern was developed by Archer (1984), who identified six types of activity as Programming, Data collection, Analysis, Synthesis, Development and Communication [18]. Cross (2000) developed a simple four-stage pattern in the design process which includes exploration, generation, evaluation and communication [17]. An iterative feedback loop is shown from the evaluation stage to the generation stage, providing an effective model to evaluate the concept. The end point of the process is the documentation and communication of a design for manufacturing.

The design process aims to figure out what is required, brainstorm innovative ideas, create new models, evaluate the design and finally generate the product. It is not a one-time process. The process of iteratively refining a design idea, making it into physical model and then evaluating its outcome to identify improvements can be described by five stages (Figure 1). There are five stages in this design process.

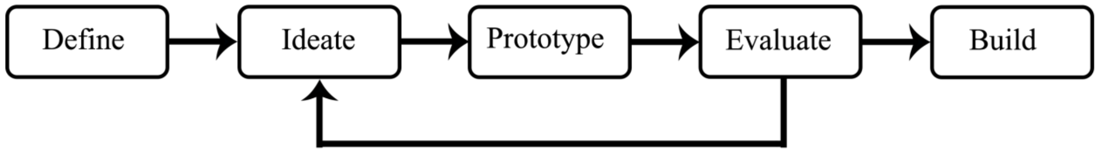


Figure 1. Flow Chart of Design Process

- **Define:** Designers must define what they plan to create and identify what users need as well as what goals they aim to accomplish. Thus, designers will set up their definitions, aspirations and goals in this stage.
- **Ideate:** Following product definition is the creation of concepts in the ideation phase. To be more specific, designers will create, draw, sketch and develop the products.
- **Prototype:** After all the concepts have been completed, it is time to establish different kinds of models. This is a skeletal system developed upon the design process. Designers will utilize different types of models to evaluate their ideas in the next stage.
- **Evaluate:** In this stage, designers employ different models to validate what the product will look like and how it is going to work. This stage also allows users to test the models. It is significant to ensure all of the features operate smoothly without any problem.
- **Build:** The build phase aims to develop the final product after designers gather all the information and feedback from prototyping.

Prototype testing refers to creating prototypes to evaluate the improvement of the concept. It has been widely used in almost every product type ranging from dog food to automobiles, from detergents to electron microscopes [23]. It will determine whether the product lives up to its promises, what the potential problems are and how the product can be improved [24].

2.2 Physical Models

As mentioned above, building models to evaluate and improve concepts is part of design iteration. Models are extremely important tools for improving the quality of design decisions [25]. It requires most of the time required for the design process. Making models has great significance [19]. Why it is so important? Using models to test the concept is the best and most efficient way to obtain answers about which concept is clearly wrong.

Designers tend to have a clear idea of how they want their product to work and what they want their product to like. However, new designs are often accompanied with unforeseen problems [1]. Making models to test helps designers to know whether the product will actually perform as desired or appear as imagined.

More specifically, different models can help designers to make adjustments to the design, materials, size, shape, assembly, color, manufacturability and strength [3]. Through providing different types of models for testing, designers can get adequate and accurate feedback. Based on this feedback, designers will know whether they need to iterate upon the design, how to improve their design or whether they can push forward to build up a more polished product. Designer may use 2D sketches as a guide when undertaking sketch modelling, but the technique is particularly suited to interactive design development, where the designer handworks the form until content with its look and feel [26].

During the prototyping and evaluation stages, a number of models are built and tested. Most of them are not made the same as the final product, as they have different aspects to test. Those physical models bring three-dimensional reality to design ideas [25]. For example, a model can be as simple as some sticks inset together with low visual fidelity. Nonetheless, such model with low visual fidelity can exhibit the construction very well. Contrarily, a perfect appearance 3D print model, which looks precisely the same as the final product, has high visual fidelity but low functional fidelity. It can help designers figure out what the product will look like, yet it has very low functional fidelity. Though these two models are made in the prototype stage, each is most effective for two different situations. Not only can designers develop a model that looks like a realistic product, but also have a prototype that works like an elastic product. These dimensions of fidelity are called “visual fidelity” and “functional fidelity” [20]. In simpler terms, they are “looks like” and “works like” models. By varying the attributes along these two dimensions, models may be divided into many types of categories [27] (Figure 2):

Concept model (3D sketch model): A crude physical model is made to demonstrate an idea. Concept models allow designers from different functional areas to understand the idea, stimulate the thoughts and discussion, as well as drive acceptance or rejection.

Design development model: Design development models are used to help understand more about the relations between components, cavities, interfaces, structure and form.

Appearance model: An appearance model has no function, even though it looks like the final product. The appearance model has many visual attributes, include color, texture, size and shape. And they are highly detailed, full-sized models.

Functional model: This kind of model will enable designers to see how the product works, and how a part or assembly functions. Some functional models make with different materials can be used to test the properties.

Concept of operation model: These help to assist the understanding of operational strategies and usage procedures relating to the product.

Assembly model: These show assembly consequences to allow assembly, cost and investments in the product to be calculated or evaluated.

Final model: A final model is very close to the final product, at the end of the cycle. It has high visual fidelity and functional fidelity, which means it has full function and complete appearance. The final model enables designers to test all the concept details in order to ensure that the model can be produced.

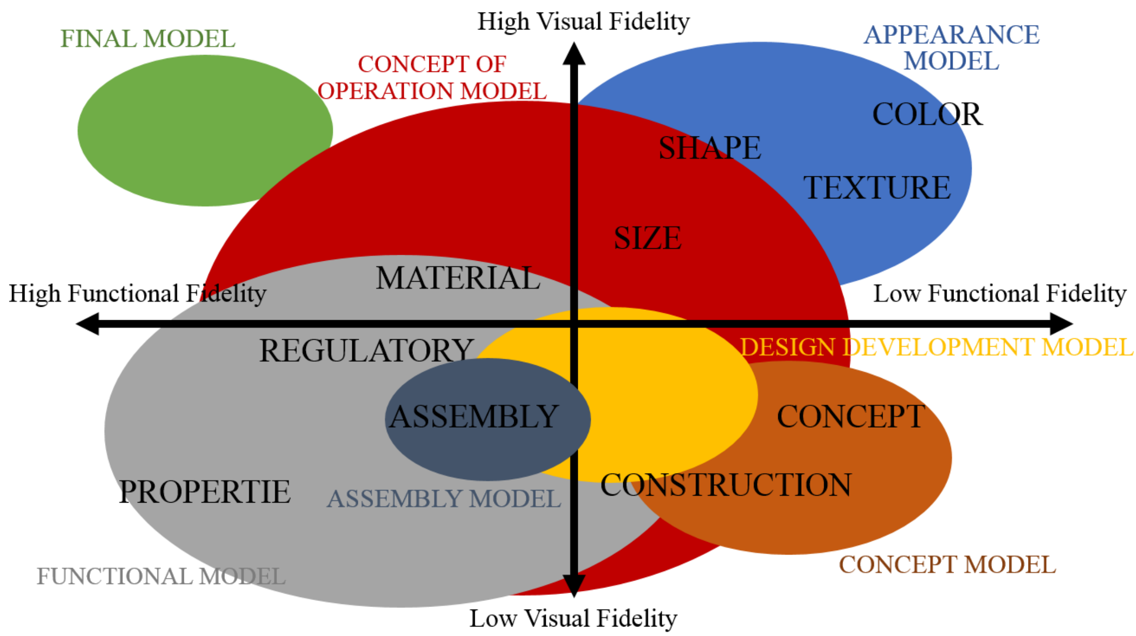


Figure 2. Types of models based on the attributes of visual and functional fidelity

2.3 Fabrication Methods

An essential steps in the design process is building a model to test design variations, test and compare theories, as well as validate design performance [2]. The above has been introduced to determine what type model should be constructed for testing different factors. Now, the remaining problem is determining which fabrication methods should be chosen when designers make different models. There are various types of fabrication process for designers to select from when they are undertaking a project. Each fabrication method has its advantages, disadvantages, and unique characteristics [10]. Therefore, choosing a proper fabrication method to complete the desired model is a crucial step.

2.3.1 Digital Fabrication

Digital fabrication is defined as a computer-aided processes that manipulates material utilizing subtractive or additive methods. The process is mechanized so that it requires very little additional guidance from the designer during fabrication [12].

2.3.1.1 Computer Numerical Control (CNC)

CNC machining produces finished parts from a variety of materials by cutting parts from blocks of the desired material via laser cutting, milling, water jet cutting and other processes. The process begins by 1) preparing a file in the computer, 2) placing the material in the machine, and 3) transferring the file to the fabricating machine. The machine automatically mills or cuts the material according to the computerized directions provided by the user (Figure 3).

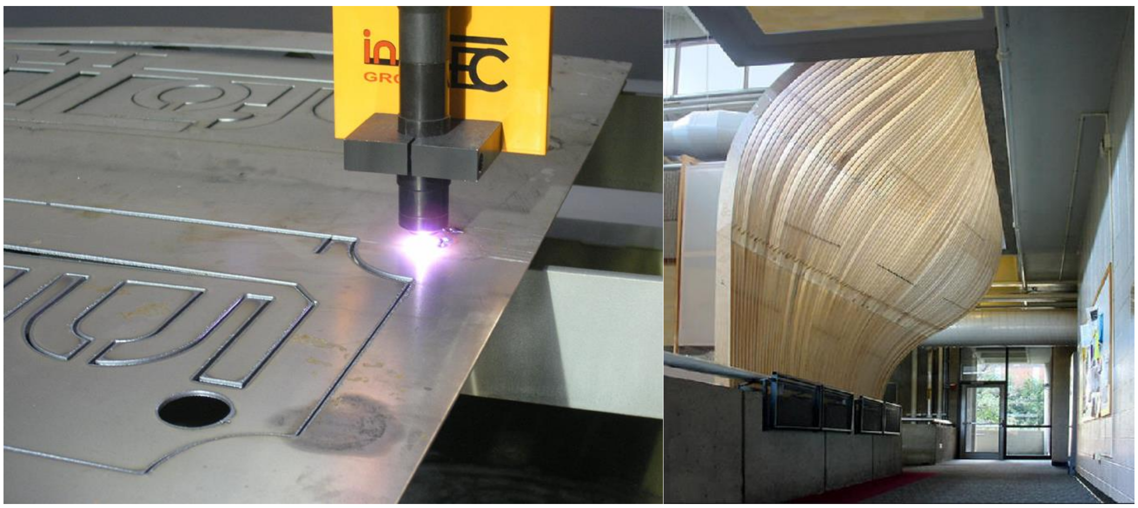


Figure 3. Computer Numerical Control

CNC machining is generally the most accurate prototyping process but requires a long lead time [10]. It can cut materials precisely and produce strong components with good surface finish, thus reducing secondary operations. It’s suitable for functional evaluation and testing.

2.3.1.2 Rapid Prototyping (RP)

Rapid prototyping is a group of techniques used to quickly fabricate a model. The process steps are as follows: 1) prepare a 3D file for the computer, 2) set up the machine, 3) send the file to be printed. The machine automatically builds up the material according to the computerized directions it is given. Rapid prototyping process starts with the creation of geometric data, which must represent a valid geometric model. The prepared geometric model is typically sliced into layers, and the slices are scanned into lines. And then it builds up a model layer-by-layer (Figure 4).

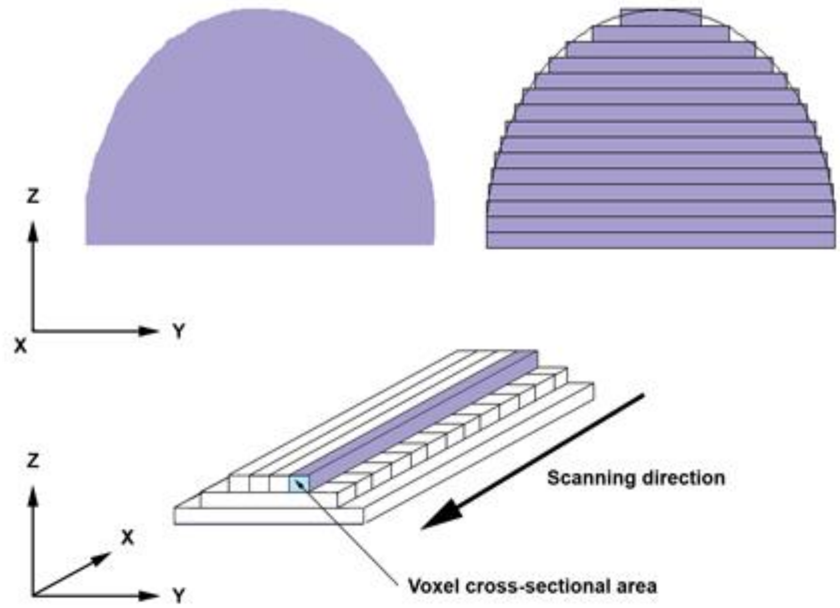


Figure 4. Rapid Prototyping Working Principle

3D printing is a process of making a three-dimensional solid object of virtually any shape from digital models. Time cost factors depend on the method used, size and complexity of the model. It can print color models. Support material is drawn where needed throughout the process [8, 13]. In the end, the models are formed from a brittle, plaster-like material (Figure 5). This method is not recommended for functional testing because of its inherent weakness.

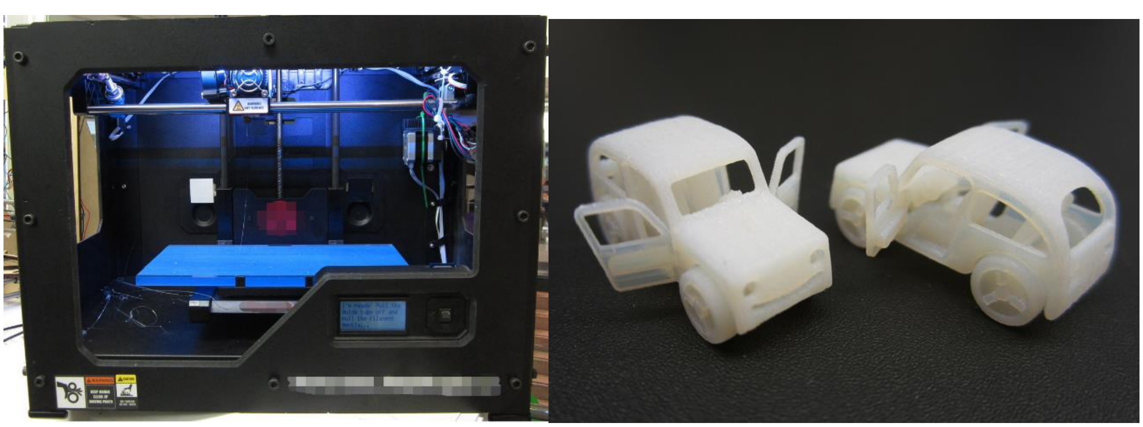


Figure 5. 3D Printing

3D printing offers the fastest build time of any additive process [3]. One characteristic is that it can print colorful models, which provide more practical information and has aesthetic appeal. The process can form parts with complex geometries. It is a very simple method to create appearance models quickly and efficiently. However, models made by 3D print process are rough and fragile. There are very few material options and the method provides no insight into the eventual manufacturability of the design [3]. Therefore, 3D printing will not be chosen when designers need a functional or finalized model.

SLA is the first RP technology used for producing models, prototypes, patterns, and production parts [11]. In the process, laser draws a layer of the desired object on the top surface of a photosensitive liquid resin, curing the top surface. Support material is drawn where needed throughout the process [3, 8].When it completed, the models are formed from a very durable, transparent resin (Figure 6).

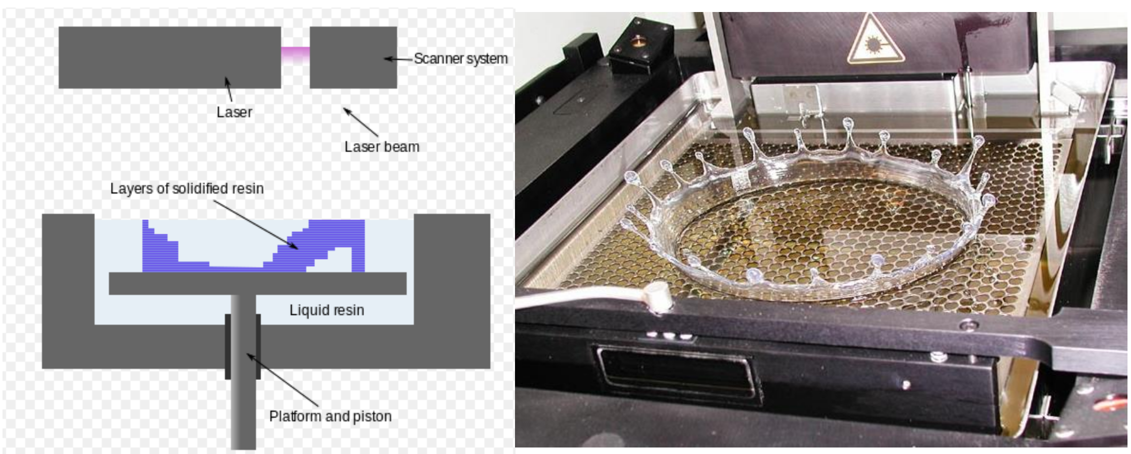


Figure 6. Stereo Lithography

SLA can produce parts with complex geometries and excellent surface finishes when compared to other additive processes [3]. SLA models can also be post-processed for varying levels of finish. The user is delivered a final product that requires less sanding. An additional advantage is its processing speed. Components can be manufactured within a day. Each of these advantages indicates that it will be an appropriate method in forming appearance models.

SLA models are not suitable as functional models, since they tend to be weaker than parts composed of engineering resins. The UV curing aspect of the process produces parts susceptible to degradation from sunlight exposure [10].

FDM processes ‘draws’ one layer of the desired object at a time with molten plastic [8]. FDM models are relatively strong and can be optimal for some functional testing. The process can produce parts with complex geometries. So, the FDM method is considered ideal for applications when functional prototypes do not require high-quality visual surfaces. FDM is also a suitable process for building assembly, testing, and inspection fixtures that would otherwise be difficult or impossible to machine [10]. However, the process is slower than SLA and SLS, and parts have a comparatively poor surface finish (Figure 7).

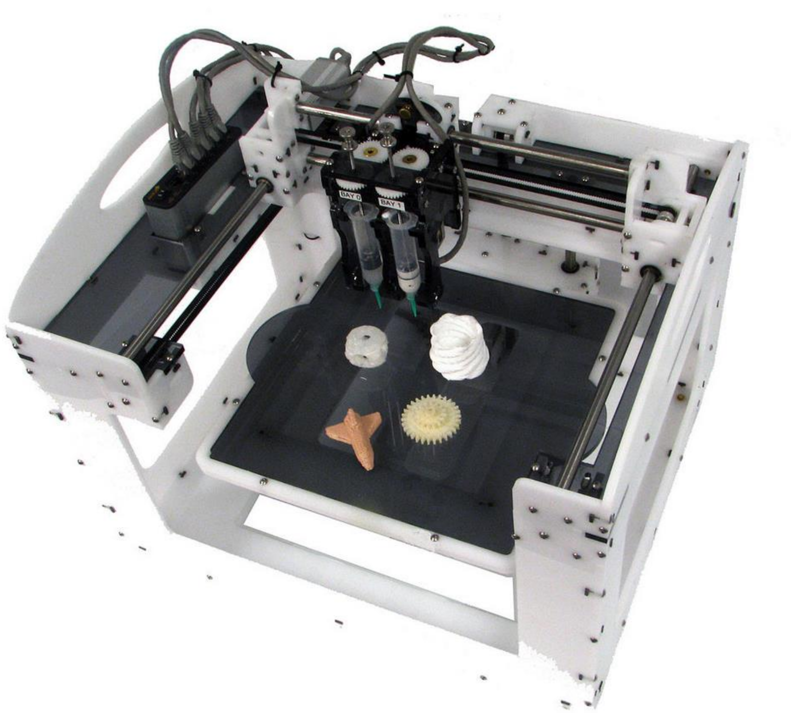


Figure 7. Fused-Deporition Modeling

Rapid Injection Molding is achieved by injecting thermoplastic resins into a mold, just as is done in production injection molding (Figure 8). The process provides a good predictor of manufacturability during production. Components can be molded from a wide range of engineering resins with excellent surface finish [8]. It is a proper choice for making multiple models. Tooling costs are higher and model forming requires more time with this method.

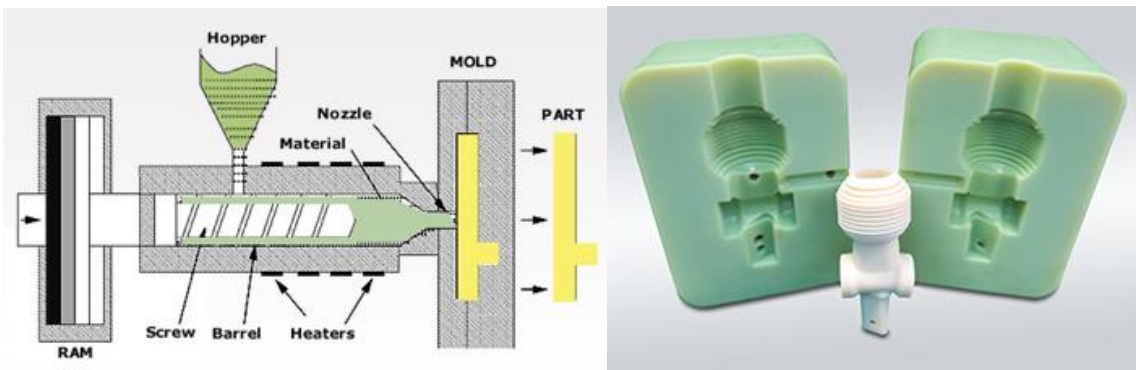


Figure 8. Rapid Injection Modeling

<u>2.3.2 Handmade Model Making</u>

Handmade model making includes using hand tools and conventional machines. Designers must manage the tools by themselves (Figure 9). In this process, model was made without computer assistance. Some people say a handmade prototype is the best method for starting the design process [1]. When compared with digital fabrication, this method is slow but offers more flexibility. When designers make concept models, they need to change the model quickly and frequently. Handmade models support this designer requirement. The disadvantages of handmade model formation are obvious; models formation offers low visual and functional fidelity for study models.

Figure 9. Hand made model making

2.4 Fabrication Method and Models

Mark A. and R. Ian's research project compared industrial design models made by rapid prototyping and workshop-based fabrication techniques. This was achieved by producing two cutter guard models with identical appearance [22]. Upon completion of the two appearance models, rapid prototyping decreased time for making components, filling, painting and assembling. However, workshop appearance models cost less than rapid prototyped models. This research identifies the advantage of rapid prototyping in the production of complicated appearance models when compared with handmade model production.

CHAPTER 3

OBJECTIVE

3.1 Objective

The objective of this paper is to investigate the relation between fabrication methods and design outcome. The relation factors include different types of models; model discrepancy by building with different fabrication methods and differentiate fabrication methods for making model. In this study, the type of model is quantitative and the variable is the fabrication method. Using different methods to build one type of model leads to different design outcomes. Each design outcome can show the feasibility for the corresponding fabrication method. This study is based on the hypothesis that there has a most appropriate fabrication method for building one type of model in design process (or "A fabrication method" is the best choice for building one type of model).

Questions about the relation between fabrication and design outcome in this study:

- Which fabrication method is the best choice for one type of model?
- What factors will influence designers to choose fabrication method?
- What types of models, which are made by different fabrication methods, are users' favorites?

3.2 Survey about choosing fabrication method in different design stages

A preliminary investigation into students' perspectives on choosing fabrication methods in early and late design stages was conducted among industrial design majors in 2013, two surveys were conducted. 56 students majoring in industrial design from sophomore to graduate level participated in these surveys. Those students already have related knowledge of industrial design, especially fabrication of models.

Students completed two surveys: the early project survey and the late project survey. The early project survey included three questions. These questions asked which current studio they were taking; what fabrication methods they used in the ideation phase of their project and the reasons for choosing the fabrication methods. After two months, all the participants completed the late project survey according to their project and experience. The late project survey included five questions: which current studio they were taking; what fabrication methods they used to create the final model in their project; the reasons for choosing the fabrication methods; how successful were the model fabrication methods they utilized in the early stages and how successful were those utilized in the final stages of their project.

A totally of 56 students joined in this study, 30 sophomores and 26 graduate students completed the surveys. Students were asked questions regarding their choice of fabrication method. In particular, they were asked which fabrication method they use to create models during the ideation phase of their most recent studio project. In the late project survey, students were asked if they prefer to use laser cutting or manual tools when building models during the early phase of a project. More than half of the students preferred 3D printing, then laser cutting and manual tools to create their final model.

These two surveys also asked students why they chose to utilize particular fabrication methods in each project phase. The results indicate that speed is the most important factor in both phases. In other words, students utilized the fabrication method that can create a model in the shortest amount of time. Therefore, time allotment is the most important factor for students when choosing a fabrication method to build a model.

Difficulty using specific fabrication methods during the early phase is more important than during the late phase. In the project's late phase, the fabrication methods that can accurately create models will be chosen preferentially.

In addition, students evaluated whether the success of each of the fabrication method, which they utilized during the early and late stages of their project, met their expectation. They rated the fabrication methods 1 to 5, 1 meaning very unsuccessful and 5 meaning highly successful. 3D printing, laser cutting and manual tools scored significantly higher than others. 3D printing, laser cutting and manual tools are the most common and effective fabrication methods used by students. Therefore, these three fabrication methods, which are 3D printing, laser cutting and manual tools, may become the main research subjects in this study.

The result of the related work shows that the most common fabrication techniques are 3D printing, Laser Cutting and Manual Tools. Therefore, these three fabrication methods will be used in this study.

CHAPTER 4

METHOD

This research is to investigate the relation between fabrication methods and design outcome. In this study, the fabrication methods included 3D printing, CNC and handmade model making. Three questions about the relation between fabrication method and design outcome would be answered. The questions are which fabrication method is the best choice for one type of model; what factors will influence designers to choose fabrication method; what types of models, which are made by different fabrication methods, are users' favorites.

4.1 Phase 1: Model Creation

4.1.1 Participants

20 Industrial design students from college are recruited to be volunteers to take part in model creation. All the participants in this study must be over the age of eighteen. In order to conduct the experiment successfully, each participant should already has industrial design related knowledge, especially fabrication knowledge. In this way, some unnecessary problems caused by the lack of expertise or professional knowledge will be greatly reduced. For instance the student might not know how to build an accurate digital model; how to use digital machine. Therefore, senior students are priority selection for this experiment. In addition, each student's skills and knowledge are different. For the purpose of ensuring the accuracy of the results, participants were recruited from similar class years. Thus, twenty volunteer students in the same grade are selected. Each participating designer was assigned a subject ID ranging from D.01 to D.20.

Even though each participant has expertise in industrial design, in order to insure the results accuracy, designers will be involved in the experiment. Designers need to have sufficient experience to deal with any kind of design condition, so that they can help students solve problems.

4.1.2 Procedure

Each participant is assigned a fabrication method to create a model based on a description of concept. A detailed project description described what needed to be built including: the product name, function, size, color, shape, texture and material. By following a description rather than a picture or a physical product, participants had latitude in how they build the model and the outcome will be more subjective.

After participants got the description. Each participant was assigned one of three fabrication methods to use: CNC, 3D Printing and Handmade model making. A fabrication method was randomly to each participant using the following procedure. Firstly, each fabrication method was written down seven times on identical pieces of paper, making a total of twenty one pieces of paper. They were the folded in the same way so that each was indistinguishable. The folded papers were mixed and one was given to each of the participants to make the model by employing the assigned fabrication method. After all the participants got their assigned fabrication method, they were required to complete the pre-survey.

Participants had three weeks to accomplish the model. During these three weeks, participants can plan their own schedule. However, their models were recorded through weekly photography and the participants were also required to report their work every week. The report included what if any difficulties they run into; whether the problems have been solved and how they solve the problems. Participants have to hand in the models and finish a later-survey in three weeks.

4.1.3 Product

The experiment is conducted based on designing a specific product. Participants need to use three different fabrication methods to create their own model of the product. As noted above, each fabrication method has its inherent advantages and disadvantages.

It means that each fabrication process may not be appropriate for different types of product models, which will cause inaccurate results. Therefore, choosing an appropriate product is the key for this experiment. It must be possible to fabricate the product used in the study by each of the three fabrication methods and the function will not affect the design for the product.

According to the fabrications analysis above, three fabrications are graded in different factors, included size, complex and material (figure 10). In figure 10, 100% means this fabrication method can build all size of model or conduct all type of material or make very complex model. 10% means this fabrication method can only build small size of model or conduct a few type of material or make simple shape of model.

CNC include laser cutting, milling and water jet cutting. It can cut virtually any material, but doesn't suit for all size material. Therefore, the percentages for material and size are 80% and 60%. CNC machining is finished parts by cutting parts, that it's hard to make complex camber. However, designers can cut many components to assembling, so it can still accomplish complex model [10]. 3D printer only can print small size parts and there are very few material options. So the size and material percentage are 10%. However, the complex score for 3D printing is 100%, because the process can make parts with complex camber. Handmade include a lot of tools and conventional machines, so that is can process all material with large size. Designers can also build complex models and camber part.

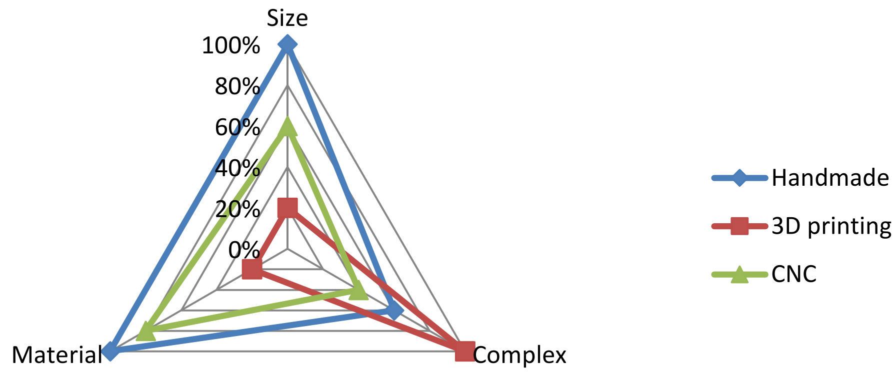


Figure 10. Characteristic of different fabrication methods

Figure 10 shows the basic characteristic of handmade, 3D printing and CNC. Each factor' lowest percentage are the requirements for the concept.

- **Size:** Model size need to be small than 26 in*14 in*22 in that can be 3D print [21].
- **Complex:** This model can be complex.
- **Material:** Model can include different materials.

Based on all the requirements, a mini-flashlight has been chosen for this study. A mini-flashlight is an appropriate size for 3D printing. It has no complex curved surface, so that it works for CNC. This product also has some details which are not too complex. The function of mini-flashlight is quite simple and un-changeable, which is good for physical design.

4.1.4 Pre-survey

Since the fabrication method to formulate model is assigned, the participants cannot choose what fabrication method they want. As they have already processed professional knowledge and experience, they may prefer a different fabrication method for making this model. In order to understand participants' perspectives, they are required to fill in a pre-survey, which includes six questions. Through asking these six questions, this survey can collect data about how participants choose a fabrication process and why.

By concluding the data form question 1: what fabrication method do you want to use for making your model in this study, the fabrication method, the most frequently selected one, will be chosen in this design stage. Question 2 in the pre-survey is why you chose this fabrication method to make you model. The factors which are selected by half participants in question 2 are the factors that participants considered. This data will answer the question about what influences designers to choose the fabrication method. Question 3 and 5 asked how successful the final model would be by using the assigned fabrication method and the personal choice of fabrication method. Data from question 3 and 6 will be referenced to compare the final result.

4.1.5 Late-survey

After finishing their models, all the participants are asked to fill in a late-survey. Participants may have different perspectives about the fabrication method and experience for making model by using the assigned fabrication method. This survey will ask participants to evaluate the level of success for their models utilizing the assigned fabrication method. Their answer may be different after they making the model with the assigned method. Besides, the participants will be asked to evaluate the level of difficulty in making the model and choose what the difficult factors are during the process of formulating the model. By asking this question, participants' perspectives about which fabrication method is helpful in making the model and the level of success will be collected. The late-survey will also ask the question about what problems participants are facing while making the model and what they want to change about the concept to improve the model with the assigned method. These two open questions will help collect the data about the advantage and disadvantage of their assigned fabrication methods.

4.2 Phase 2: Model Evaluation

4.2.1 Participants

In order to evaluate the models, forty people aged above eighteen years will be recruited in this study. When people volunteer in this study, they will be assigned with an evaluator account (E.01 to E.40). Forty evaluators are further divided into four groups randomly, and each of these groups consists of ten evaluators.

4.2.2 Procedure

The 20 models, which collected in model creation, would be given numerical tags ranging from one to twenty. The model's tag number is the same as their designer account (D.01 to D.20). After all the models have been distinguished with a numbered tag, a spreadsheet of each model, their respective number tag, and method of fabrication will be recorded and only can be seen by the administrator for confidentiality.

After this process, the models will be mixed. Meanwhile, forty evaluators will be ready to evaluate these models. They will be randomly designated five models and they will only evaluate the five models that have been assigned to them.

When evaluators are presented models to evaluate their models to evaluate, they will receive a description of the product and its usage. Based on this description and the models, evaluators have to finish an evaluation-survey consists of 8 questions for each model. Therefore, each evaluator will complete 5 evaluation-surveys in total.

4.2.3 Evaluation Survey

The evaluation-survey included eight questions. After evaluators understood the description for the models, they were asked to rate to what degree the model meets the description in each aspect. This survey will collect evaluators' perspective, such as whether they like the model's appearance and if they want to buy this type of product. The last question in the evaluation-survey is an open question about what evaluators wish to change or improve in the model. The result of this question may help designers to improve their concepts.

CHAPTER 5

RESULTS

The experiments were accomplished in two months. Model creation took one and a half months. In this phase, twenty industrial design students used three different fabrication methods to make twenty mini-flashlight models. Each student filled in a pre-survey before they made the model and a later-survey after they built the model. Forty surveys were collected in this phase. Model evaluation took two weeks. Two hundred surveys were collected to evaluate those twenty mini-flashlight models.

5.1 Model Creation Results

The results of model creation include three parts: Pre-survey data, Late-survey data and the physical models that were created. There were 6 participants used laser cutting to build the model. 7 participants made the model by using 3D printing and other 7 participants built the model by using handmade model making.

5.1.1 Pre-survey Results

The pre-survey included six questions (Appendix A). Question one to three asked participants' personal opinion regarding which fabrication method they wanted to use for making the mini-flashlight model, why they chose this fabrication and the success rate for the fabrication.

Figure 11 shows that one participant chose CNC (Computer Numerical Control) to build the model due to the complexity of the model. More than a half of participants chose to employ rapid prototyping to make the mini-flashlight model as they thought that using it to make mini-flashlight would be faster and that this fabrication method would be suitable for the model's complexity and finish surface (Figure 12).

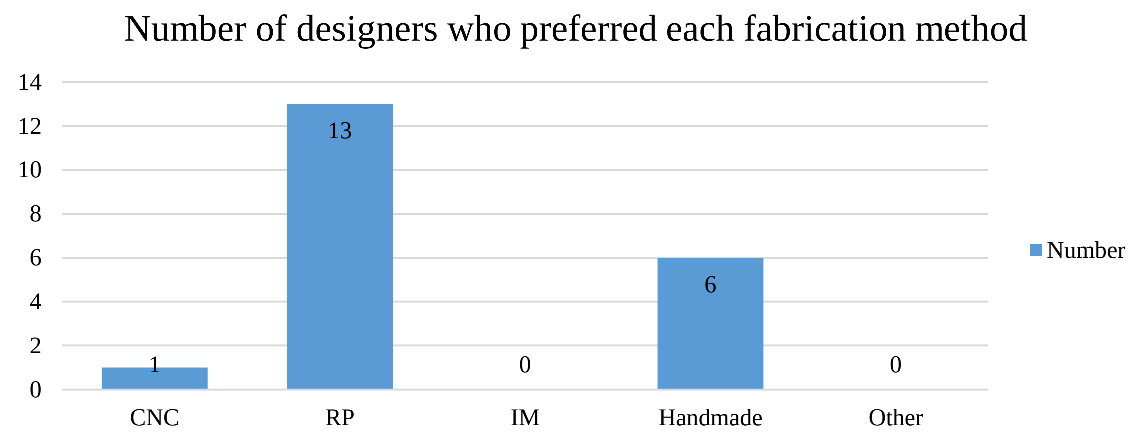


Figure 11. Number of designers who preferred each fabrication method

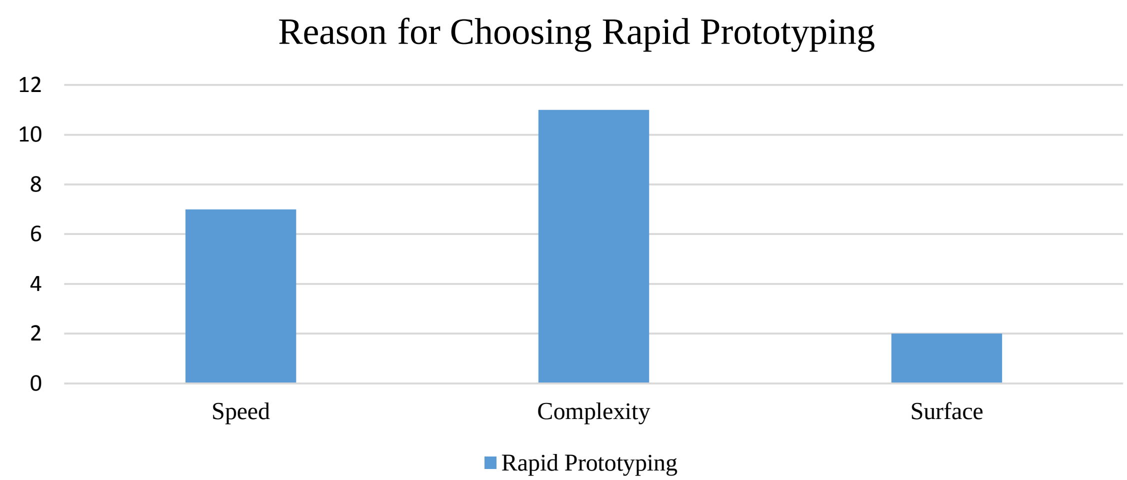


Figure 12. Reason for choosing Rapid Prototyping

There were various reasons for those six participants to choose the handmade model making, such as speed, quantity, complexity, material, finish surface, flexibility and adjustability (Figure 13). As for choosing this fabrication method, speed and quality are the most important reasons. Participants only need to make one model; therefore, they thought handmade model making would require less time for building the model. Two participants said handmade model making is flexible. When they were building the model by using handmade model making, it's easy for them to make adjustments to the model.

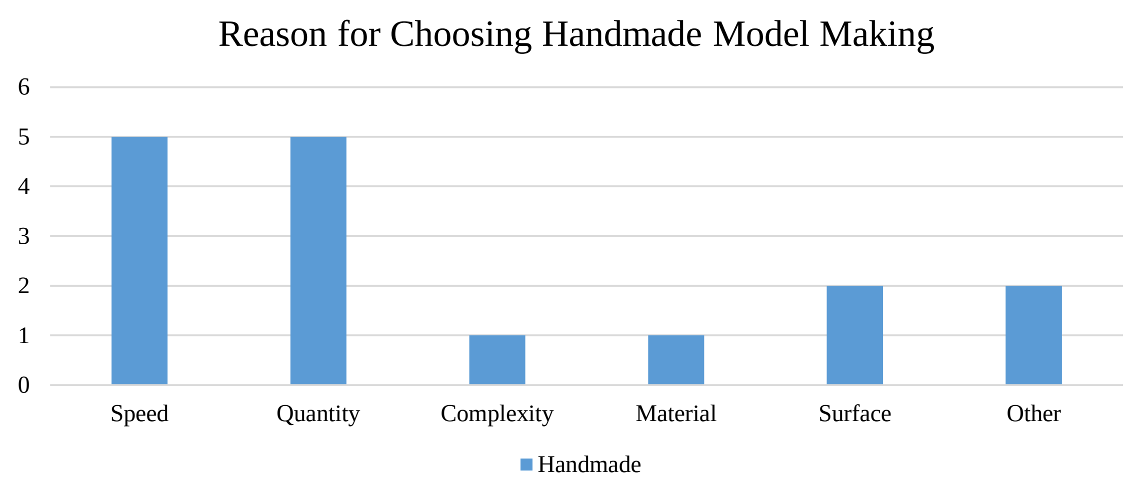
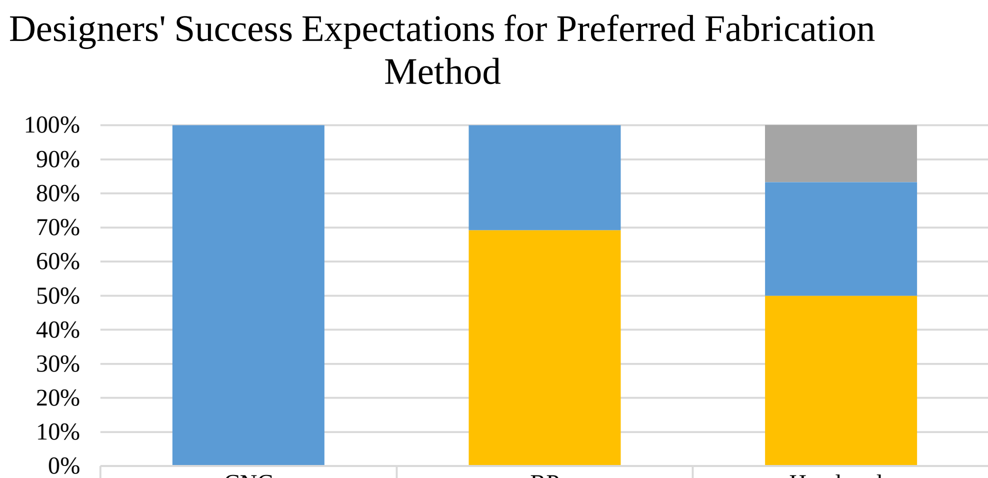


Figure 13. Reason for choosing Handmade Model Making

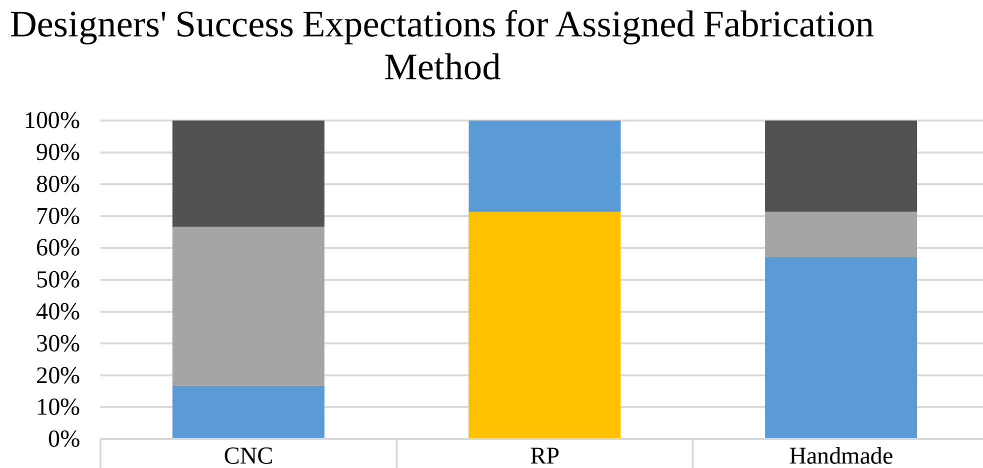
According to Figure 14, participants thought the rapid prototyping is the most successful fabrication method for making the mini-flashlight model. Nine of thirteen participants, thought the model would very successful by using this fabrication method. Other four participants thought the model would be successful by using rapid prototyping. For the six participants, who chose handmade model making, half of them thought the model will be very successful and two participants thought it would successful. Even one participant thought it was neither successful nor unsuccessful, the average of success rate is still higher than that of CNC. In conclusion, the ranking about success rate is: rapid prototyping ＞ handmade model making ＞ computer numerical control.



	CNC	RP	Handmade
General	0	0	1
Successful2	1	4	2
Very Successful	0	9	3

Figure 14. Designers' Success Expectations for Preferred Fabrication Method

After being assigned a fabrication method, twenty participants are also asked to rate how successful the fabrication method would be for building the model. Figure 15 lists the result of question 5 in pre-survey, which is rate how successful the final model would be by using the assigned fabrication method. Computer numerical control still get the lowest score, as two participants thought using CNC to make their model would be unsuccessful and three participants thought it was neither successful nor unsuccessful. Only one participant thought the model would successful if she used CNC. The score of rapid prototyping is much higher than that of other two fabrication methods, since it has five “very successful” and two “successful”. Four participants gave “successful” to handmade model making and one participant thought it was neither successful nor unsuccessful. The other two participants thought the model will be unsuccessful by utilizing handmade model making.

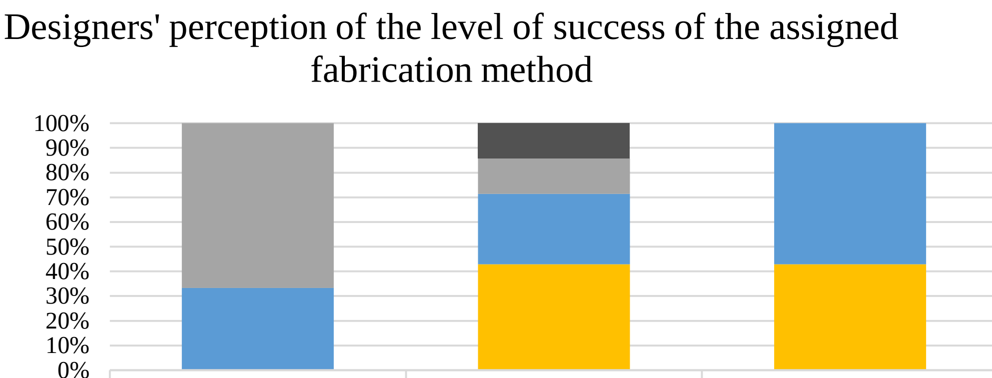


	CNC	RP	Handmade
Unsuccessful	2	0	2
General	3	0	1
Successful2	1	2	4
Very Successful	0	5	0

Figure 15. Designers' Success Expectations for Assigned Fabrication Method

5.1.2 Late-survey Results

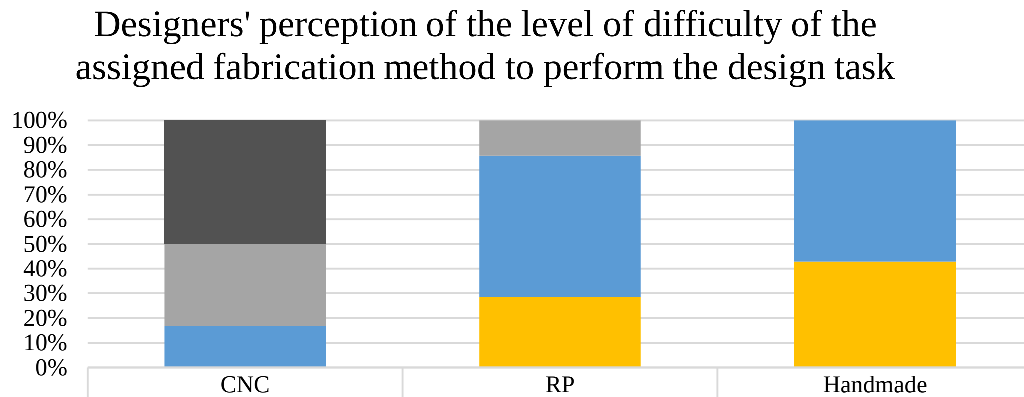
After making the model, the participants were asked to fill in the late-survey (Appendix B) based on the model and the process of making the model. Figure 16 shows the result of question 2, which was how successful the final model is. Same as question 5 in pre-survey, CNC gets the lowest score as five participants thought it was neither successful nor unsuccessful. Only two participants thought their models were successful. Before participants made the model, rapid prototyping was expected to be more successful than other models which make by handmade model making. However, the results were not as expected. Amongst the seven participants who used rapid prototyping to make the model, three of them thought their models were very successful and two participants thought the models were successful. One participant thought the model was neither successful nor unsuccessful and one participant thought her model was unsuccessful. Handmade model making got a very high score after participants completed their models. Four participants thought their models were successful. The other three participants thought the models were very successful. Ranking of the success rate changes after models were completed (handmade model making ＞ rapid prototyping ＞ computer numerical control.)



	CNC	RP	Handmade
Unsuccessful	0	1	0
General	4	1	0
Successful2	2	2	4
Very Successful	0	3	3

Figure 16. Designers' perception of the level of success of the assigned fabrication method

Figure 17 shows that the ranking of difficulty rate is the same as the success rate (handmade model making ＞ rapid prototyping ＞ computer numerical control). CNC is the most difficult fabrication method used by participants to make mini-flashlight model. Three participants felt that the method is difficult; only one participant thought that it was easy and other two participants thought it was neither difficult nor easy. Handmade model making was the easiest one of these three fabrication methods. Amongst the seven participants, who were assigned rapid prototyping, four of them felt it was relatively easy to make the mini-flashlight model by this fabrication method. Two participants thought it was very easy and one participant thought it was neither difficult nor easy. Seven participants used handmade model making to build the model. None of them felt it was difficult to make the model. Four participants thought it was easy and three participants felt it was very easy.



	CNC	RP	Handmade
Hard	3	0	0
General	2	1	0
Easy	1	4	4
Very Easy	0	2	3

Figure 17. Designers' perception of the level of difficulty of the assigned fabrication method to perform the design task

There are many reasons that made CNC become the most difficult fabrication method to build mini-flashlight model. Figure 18 lists the difficulty factors, such as speed, quantity, complexity, surface etc. More than half participants thought CNC takes too long to make the model. As the model has some details, participants felt that is difficult for them to use CNC to build it. The surface machining is difficult as well. There have been reports reflecting that assembly is also a problem when making a model by using CNC. One participant comments ‘there are too many components that I need to assemble. So it costs me a lot of time.’

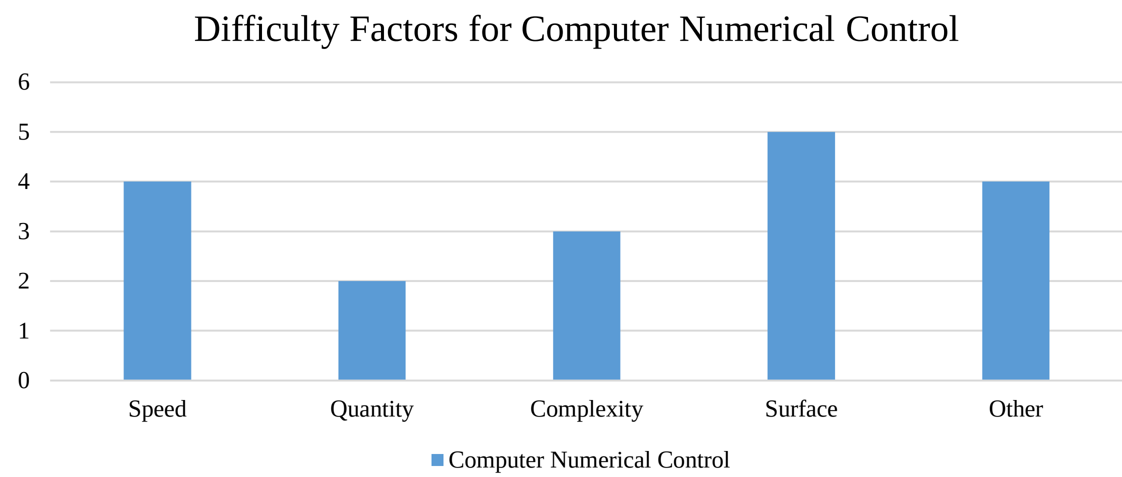


Figure 18. Difficulty factors of computer numerical control

Figure 19 shows that the most difficult factor for rapid prototyping is finish surface. As a consequence of printing precision, participants have to polish the model, which requires lots of time. Some participants thought it takes too long to make the mini-flashlight by using rapid prototyping. Two of seven participants felt complexity of the model is a difficult point. Three participants experienced painting problems as the model was small and had a lot of details. The 3D printed model is self-contained, therefore, participants must use tape to mask areas of the model that will be different colors.

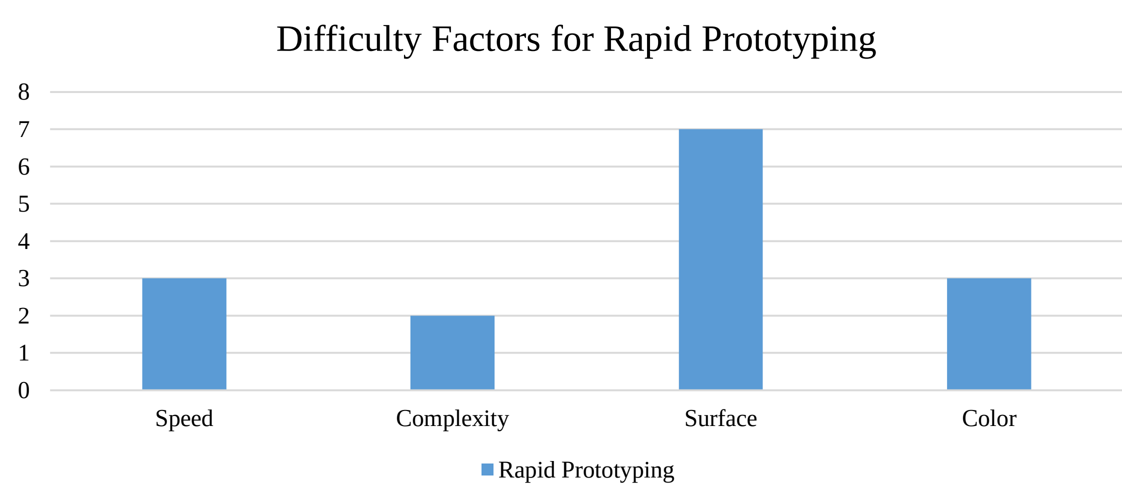


Figure 19. Difficulty factors for rapid prototyping

There are three difficulty factors for handmade model making, including complexity, surface and color (Figure 20). Almost all the participants felt the mini-flashlight model was too complex to make by hand as the mini-flashlight model has a lot of details. Only one participant experienced painting problems and the other participants felt that the surfaces were too difficult to finish.

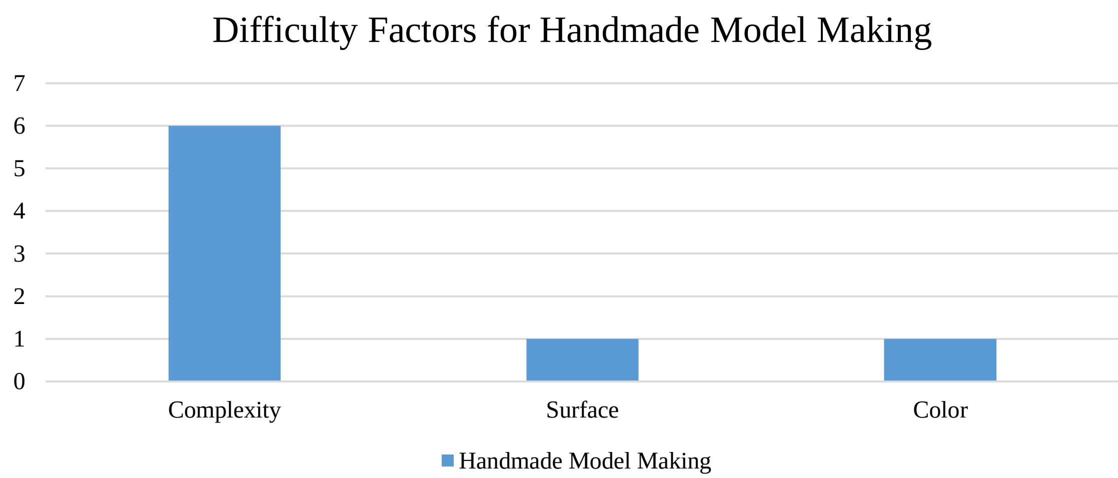


Figure 20. Difficulty factors for Handmade Model Making

5.1.3 Produced Models

These six models in figure 21 were made by CNC. All the six participants used laser cutting to make the mini-flashlight model (Figure 22) as they thought comparing with other computer numerical control methods, such as milling, water jet cutting and wood router, laser cutting is more efficient. They didn't need to build the digital 3D model and set up data. In these six models, four of them assembled layer by layer. For this reason, some participants said assembly of parts cost them a lot of time. Besides, the pieces overlapped very well, so that they had to spend time to effort to smooth the surfaces of the model.

Figure 21. Models created using Computer Numerical Control

Figure 22. Process using laser cutting to fabricate the mini-flashlight model

In Figure 23, seven models made by rapid prototyping are shown (Figure 24). The most common complaint from feedback was the precision of 3D printing models. Almost all of the models were polished. The details of rapid prototyping models were more than other models, made by CNC or handmade model making. These three reasons increase the difficulty of painting. It can be seen from figure 8.3, some models have yellow thin lines and small buttons.

Figure 23. Models created using Rapid Prototyping

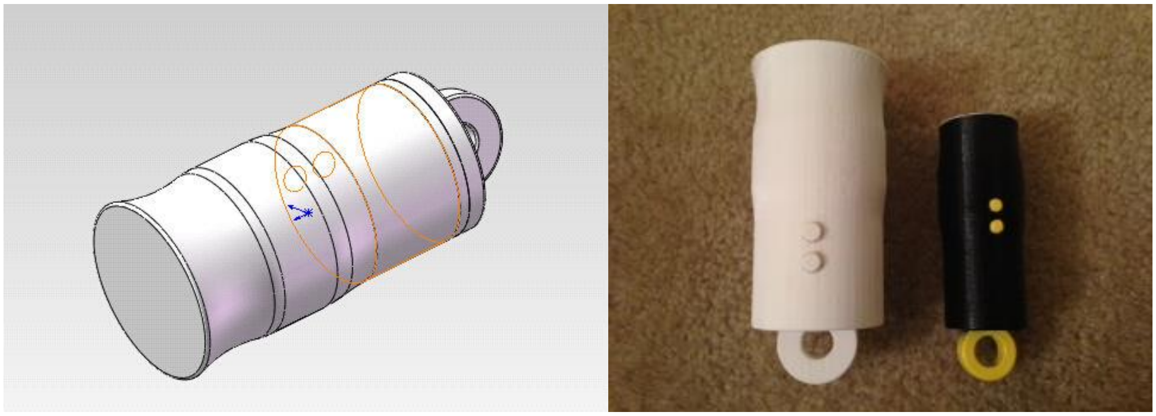


Figure 24. Process of making 3D printed mini-flashlight model

According to participants' feedback, the handmade models are more successful and easier to fabricate than expected (Figure 26). Figure 25 shows those seven handmade mini-flashlight models. When participants were asked what problems they faced when making the model. Five of seven participants said they didn't have any problem when they were making the model. One of them said: "Making mini-flashlight model by using handmade model making is much easier than I thought."

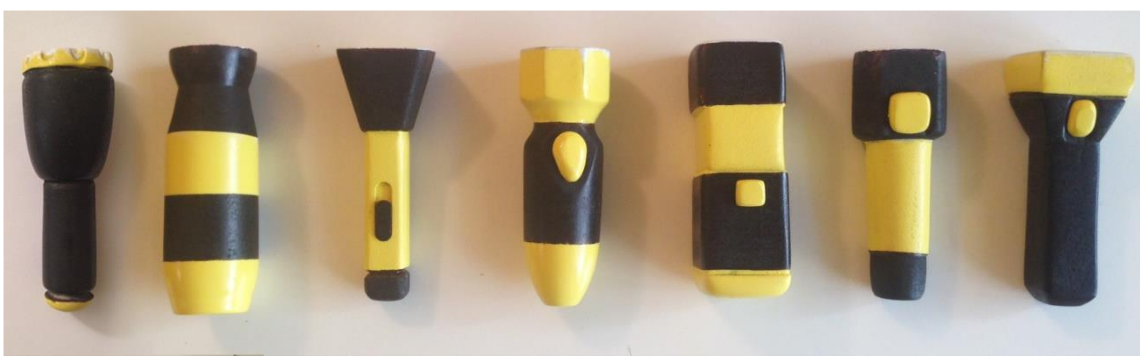


Figure 25. Models created using Handmade Methods

Figure 26. Process of making handmade mini-flashlight model

Figure 27 lists the amount of time spent in making each model by using different fabrication methods. Although there are individual differences, handmade model making required the least amount of time. Most participants required less than 8 hours to complete the mini-flashlight model. The average time for participants to make the model by handmade modeling was 8 hours. As a result of different concepts, time spent in making models by using CNC were great difference. The shortest time is 7 hours and the longest time is 20 hours when utilizing CNC to build the mini-flashlight model. The average time was 12.7 hours, which was close to average time for using rapid prototyping. The average time for participants to make the model by rapid prototyping was 11.4 hours. Six of seven participants completed their model in around 11 hours. Ranking the time spent in making the model by different fabrication methods is: computer numerical control (12.7 hours) ＞ rapid prototyping (11.4 hours) ＞handmade model making (8 hours).

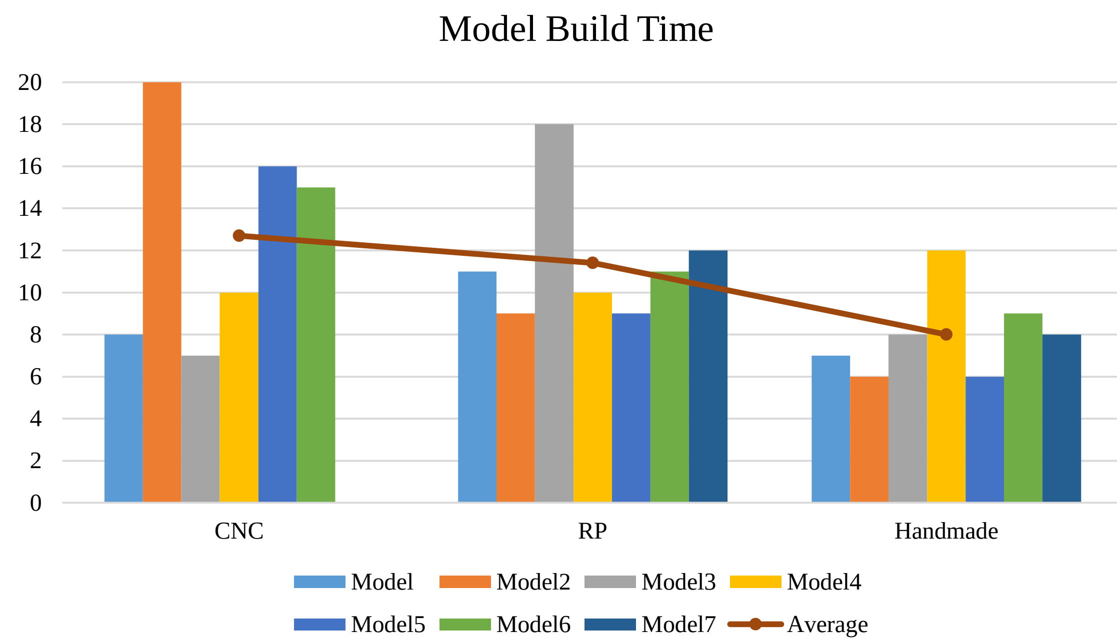


Figure 27. Model Build Time

5.2 Model Evaluation Results

Forty people aged above eighteen years were recruited to evaluate the models. Each model has the corresponding number (Figure 28) and those twenty models are taken and mixed together. Those six models number 1, 2 6,10,16,17 are made by laser cutting. The seven 3D printed models number are 3, 7, 8, 9, 14, 18, and 20. Number 4, 5, 11, 12,13,15,19 models are made by handmade model making. Each evaluator was randomly assigned five models and five evaluation-surveys (Appendix C). They completed an evaluation survey for each model. The model's number was recorded on the survey. As a result, a total of two hundred evaluation surveys were collected in this experiment.

Figure 28. Models' corresponding number

Question#1 in evaluation survey was rate the model on a scale of 1 to 5 for five aspects. 5 meaning they are very satisfied with the aspects, which including function, size, shape, texture and material. At the end of this question, evaluators need to give an overall score for the model. Each model was evaluated ten times. Table 1 lists the average for each model.

Table 1. Average evaluator rating of the level of satisfaction with various model attributes (question#1 in evaluation-survey)

Number#	Fabrication Method	Function	Size	Shape	Texture	Material	Overall
1	Laser Cutting	3.8	3.3	2.6	3.8	3.7	3.4
2	Laser Cutting	4.3	4.1	3.4	4.0	4.0	3.8
3	3D Printing	4.0	4.6	4.7	4.3	4.1	4.5
4	Handmade	3.8	4.1	4.3	4.2	4.1	4.2
5	Handmade	3.2	4.8	3.9	3.9	3.7	3.7
6	Laser Cutting	4.3	4.6	3.9	3.8	4.0	4.1
7	3D Printing	3.5	3.5	3.1	3.8	3.8	3.7
8	3D Printing	3.9	3.9	4.5	4.3	3.9	4.0
9	3D Printing	4.0	3.4	4.6	4.2	4.0	3.8
10	Laser Cutting	4.6	4.6	3.3	3.4	3.6	3.8
11	Handmade	4.2	4.6	4.0	4.4	4.5	4.4
12	Handmade	4.5	4.0	4.6	4.7	4.4	4.7
13	Handmade	4.0	3.5	3.7	3.7	3.5	3.8
14	3D Printing	4.0	4.1	3.9	3.8	3.8	4.1
15	Handmade	3.9	4.1	4.0	3.8	3.4	4.0
16	Laser Cutting	3.8	4.0	3.3	3.7	3.8	3.6
17	Laser Cutting	4.5	4.3	3.8	3.8	4.0	3.9
18	3D Printing	3.9	4.2	4.0	3.9	3.9	4.1
19	Handmade	4.2	4.2	4.7	4.2	4.3	4.5
20	3D Printing	3.3	3.9	3.9	4.4	4.1	3.9

The rating of laser cut models was shown in Figure 29. The average of rate for function and size is around 4.25 point. However, the rating for “shape” was very low. Evaluators were dissatisfied with laser cutting models’ shape. A lot of feedback imply they wanted to change the sharp edges, which may hurt their hand. The average of texture rate and material rate is around 3.75. The overall rate of the laser cutting model is 3.76.

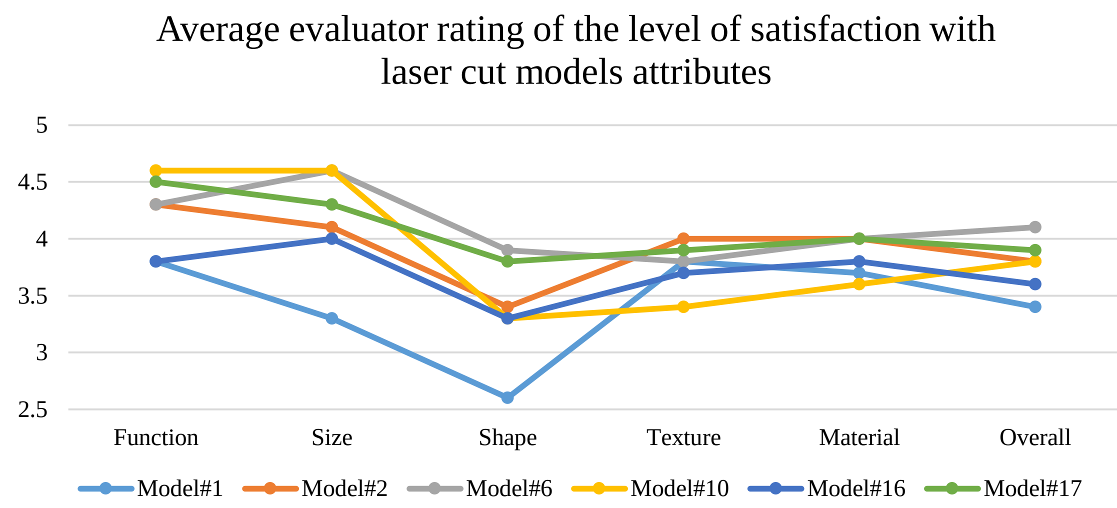


Figure 29. Average evaluator rating of the level of satisfaction with laser cut models attributes (question#1 in evaluation-survey)

Figure 30 shows the rate of seven 3D printing models on all aspects. The average of 3D printing models' function is 3.80. The size rating of more than a half of models was around 4 and only one evaluator rated the shape of 3D printing models under 3.9. It means that the size and shape of 3D printing models are suitable in general. The rating of models' texture and material is around 4.25. In overall, the average for 3D printed models is 4.01. This result shows that evaluators are generally satisfied with 3D printed models. Considering these five aspects, evaluators gave an overall rating of around 4.

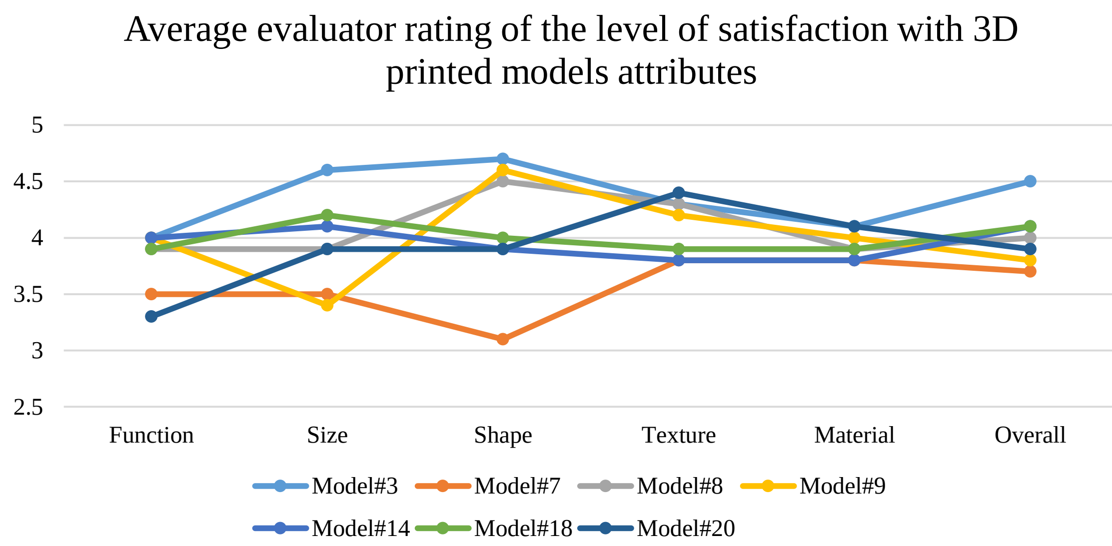


Figure 30. Average evaluator rating of the level of satisfaction with 3D printed models attributes (question#1 in evaluation-survey)

As shown in Figure 31, the ratings of handmade models was dispersive. In general, they were between 3.5 and 5. Most evaluators thought the function, size and shape of handmade models were great, as most rates were around 4. As for handmade models, the rate of texture and material was a big difference. The average rates of texture and material were 4.13 and 3.99 respectively.

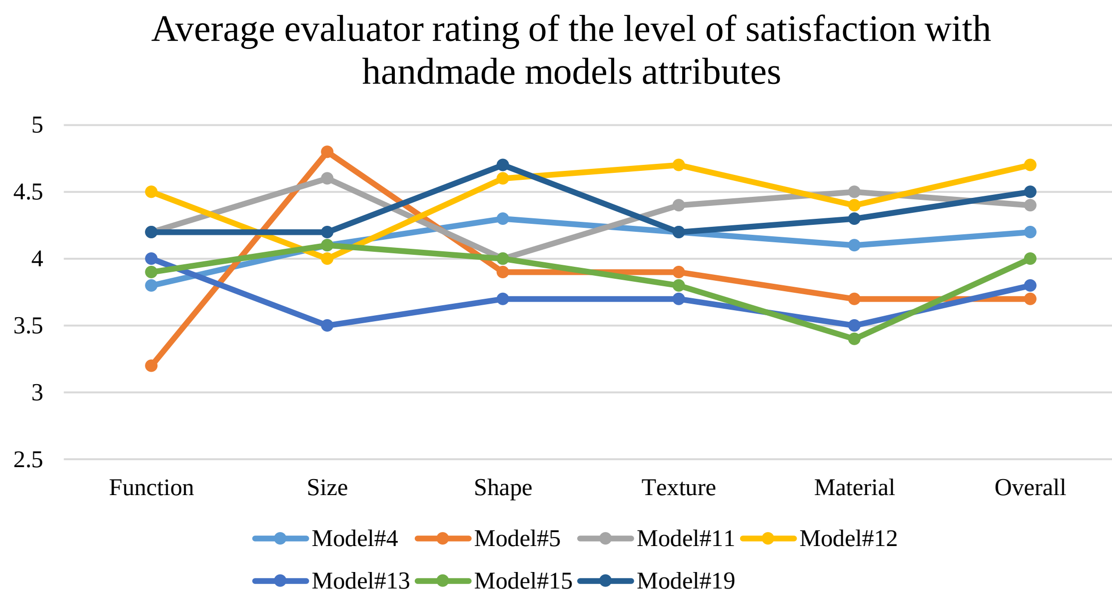


Figure 31. Average evaluator rating of the level of satisfaction with handmade models attributes (question#1 in evaluation-survey)

Question#2 and 3 ask about models' refinement and appearance. Evaluators rated the mode from 1 to 5, 5 meaning that the model was very refined or they like the model's appearance very much. Table 2 to 4 show the score for each model. Judging from these figures, it can be seen that the laser cut model scores are generally lower than the scores of other two types of models in both questions. The average refinement of laser cutting model is 3.53. However, at this point, the average of 3D printing models and handmade models score are also above 4. It means that the laser cut model was rougher than other models. Laser cut models also get the lowest average score (3.52) of these three fabrication methods. Evaluators did not prefer the appearance of laser cutting models.

Table 2. Average of each laser cut models' refinement and appearance

Laser Cut Model Number	Refinement	Appearance
1	3.2	2.6
2	3.6	3.8
6	4.0	3.8
10	3.2	3.3
16	3.4	3.5
17	3.8	4.1
Average	3.53	3.52

Table 3 lists the average of each 3D printing model in terms of refinement and appearance. 3D printed models have the highest score (4.13) in question#2. The feedback from forty evaluators show that 3D printed models are preferred by most participants for modeling refinement. 3D printed models are the only type to be rated above 4 for appearance. Most evaluators like the appearance of this type of model.

Table 3. Average of each 3D print models' refinement and appearance

3D Print Model Number	Refinement	Appearance
3	4.4	4.6
7	3.6	3.9
8	4.1	4.3
9	4.1	4.0
14	4.1	4.0
18	4.5	3.9
20	4.1	3.8
Average	4.13	4.07

Table 4 shows that the average score for refinement and appearance for each handmade model. Handmade models are refined, as the average of this type of model is above 4. The score (4.01) is close to the score of 3D printing models. However, the 3D printing models are a little more refined than handmade models. The average rating for handmade models' appearance is between the other two types of models. The average is 3.79, which means evaluators like the appearance of the handmade models, but they are not the evaluators' favorite.

Table 4. Average of each handmade models' refinement and appearance

Handmade Model Number	Refinement	Appearance
4	4.1	3.5
5	3.9	3.7
11	4.1	4.0
12	4.6	4.2
13	3.2	3.4
15	3.9	3.7
19	4.3	4.0
Average	4.01	3.79

According to Figure 32, it is very easy to understand how to use laser cut and handmade models by simply looking at model. Evaluators rated the model 1 to 5. 5 meaning that's easy to know how to use the product by looking at the model. Their average scores were 4.58 and 4.50. Although the 3D printing model gets a high score on its appearance, it's a little difficult for evaluators to know how to use it by looking at the model. Evaluators said the 3D printed models are complicated. The details confused them to found where the button was. Therefore, they thought the 3D printed models were not very easy to use. The average of 3D printed models is 4.14.

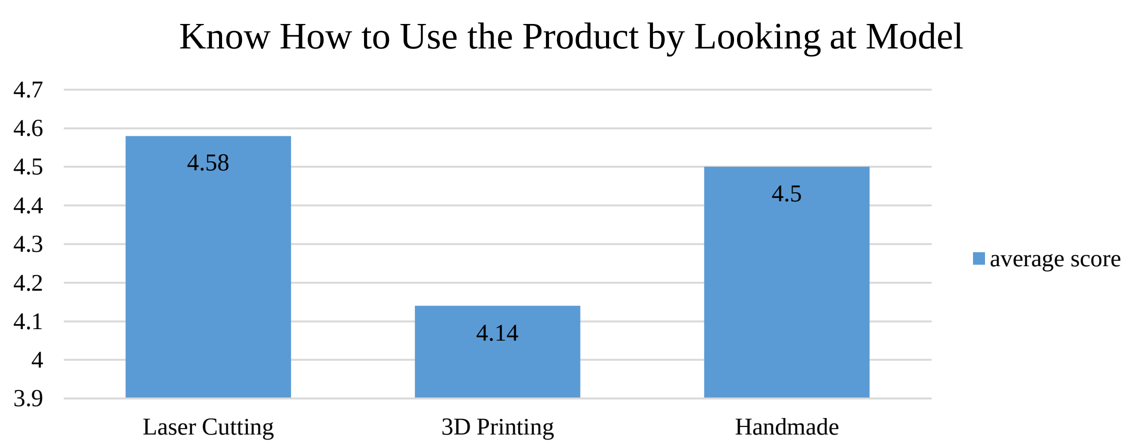


Figure 32. Average of each type models for question#4 in evaluation-survey

Question#5 in the evaluation survey asked was the product easy to use? Ranking 5 means the product is very easy to use and ranking 1 means the product is very hard to use. This question discusses whether the product is easy to use. As seen in Figure 33, it's not easy for evaluators understand how to use models made by 3D printing. Some evaluators said they cannot found the button or not sure whether it is the button. They have to use the mini-flashlight by trying. The average of 3D printed models was 4.40. Laser cut models were the easiest type of model to use, which was 4.75 point. Almost all evaluate thought they are very easy to use. In this question, the average of handmade models was 4.63. Because a few evaluators said the grip is too small to hold. Handmade models are harder to use than laser cut models, but easier to utilize than 3D printed models.

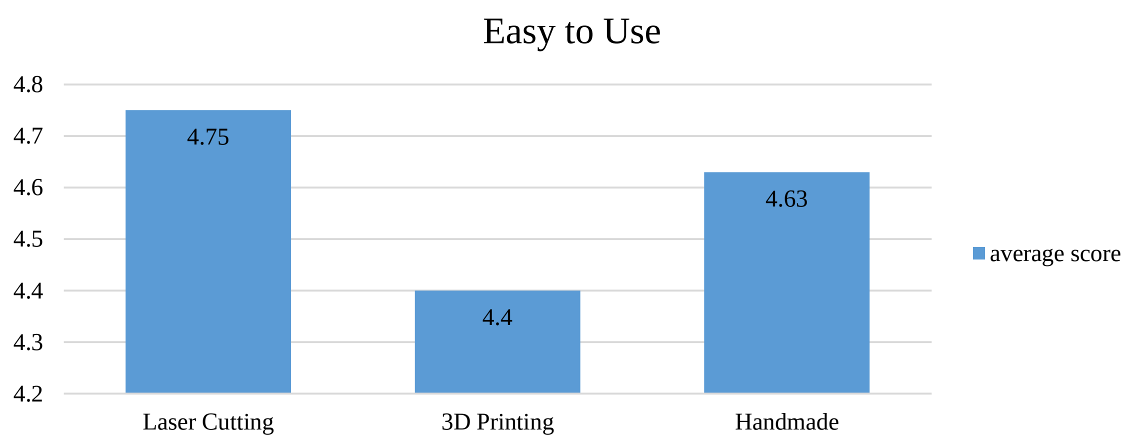


Figure 33. Average of each type models for question#5 in evaluation-survey

Figure 34 shows the result of question#6 (Do you think the product is useful). Evaluators answered this question by rating the model 1 to 5, 5 meaning the product was very useful. Evaluators thought laser cut models were useful, therefore, the average of laser cut models was 4.40. The average score of this question was close. 3D printed models and handmade models were lower than laser cut models, which were 4.31 and 4.33. On the whole, evaluators thought all models are useful.

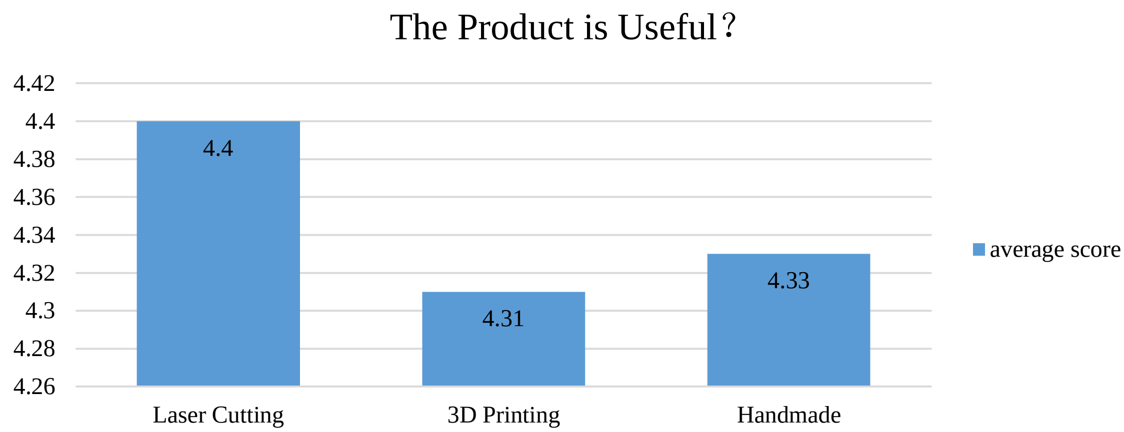


Figure 34. Average of each type models for question#6 in evaluation-survey

In Question#7, evaluators aim to know whether the participants want to purchase this product by rating the model from 1 to 5, 5 meaning they really want to buy this product. The results of this question is showed in Figure 35. The average for this question is below 3.5. It means that evaluators don't want to purchase the models, especially laser cut models. The average of laser cut models is 2.93. Few evaluators wanted to purchase 3D printed models so that the 3D printed models gets 3.36. The average of handmade models is close to that of the 3D printing models, which is 3.24.

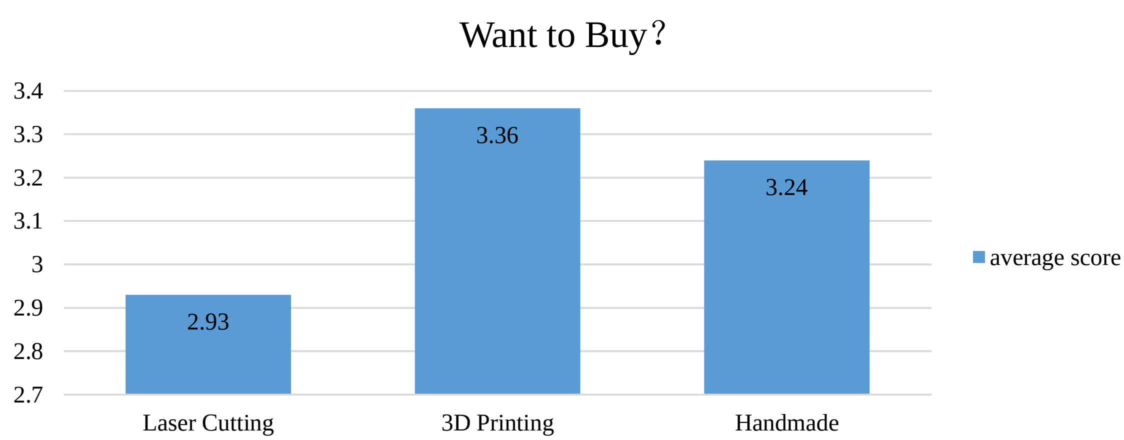


Figure 35. Average of each type models for question#7 in evaluation-survey

CHAPTER 6

DISCUSSION

The present study results contain feedback from both designers and users, and the answers to the questions posed in the section of objective in light of the findings of this study can be considered.

6.1 Questions in the study

6.1.1 Which fabrication method is the best choice for mini-flashlight model?

The fabrication method expected to be most preferred by designers was handmade model making, instead it was found 3D printing. From the result of model creation in this study, it can be seen that the most preferred fabrication method for making the mini-flashlight mode is not the anticipated one. The success rate changes in three stages: predictable success rate for the participants' idealistic fabrication method, predictable success rate for the assigned fabrication method and success rate for the assigned fabrication method. There are three questions (Question #3 in pre-survey, Question #5 in pre-survey and Question#2 in late-survey) for the three stages respectively in Experiment #1. Participants rate the fabrication method by choosing one among the five options ranging from "very successful" to "very unsuccessful". Different points are set for the choices, as shown in Table 5, and the total points were calculated according to participants' choices. The totals for different fabrication methods were calculated. The formula is shown as follows:

$$A = \frac{S}{N}$$

A=average

N=the number of terms

S=the sum of the numbers being averaged

For example, for Question#2 in late-survey, a total of 7 participants rated rapid prototyping (N=7). 3 participants chose "Very successful", 2 participants chose "Successful", 1 participant chose "General" and 1 participant chose "Unsuccessful" (S=3*4+2*3+1*2+1*1=21). Therefore, the average success rate for rapid prototyping was 2 (A=21/7=3).

Table 5. Points for the choices (How successful)

Selection	Very Successful	Successful	General	Unsuccessful	Very Unsuccessful
Points (P)	4	3	2	1	0

Figure 36 shows the average of the success rate for models with different fabrication methods at three stages. Rapid prototype models got the highest score for the first two stages, which illustrates that rapid prototyping was the best fabrication method for making mini-flashlight models in the opinion of the 20 participants. Most of them thought that the models would be very successful. It was a subjective result based on the experience and preference of the participants. On the contrary, CNC models got the lowest score at the first two stages; 6 participants rated their models with the assigned fabrication method during the second stage. It means that most participants thought that the model would be unsuccessful with CNC. However, the outcome was beyond expectation. After the 20 participants completed the mini-flashlight models with their assigned fabrication methods, the handmade models got the highest score, even though participants thought that the models obtained through handmade modeling would be neither successful nor unsuccessful. After handmade models were completed, most participants rated the models as "very successful", which was the same as the expected result of the CNC models.

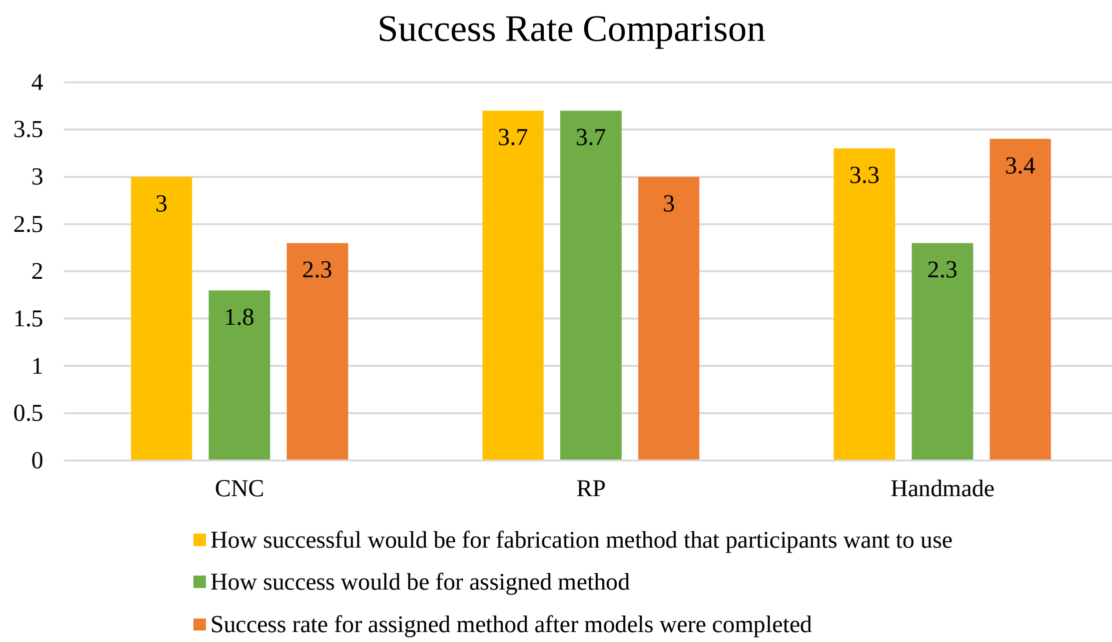


Figure 36. Success rate comparison

The averages of success rate in different stages shows that the fabrication method, which designers want to use for making the mini-flashlight model, didn't get the highest score after the models were made. Participants, who chose or assigned rapid prototyping, thought the model would be very successful before they made it. They rated the model base on their experience and prediction. However, the success rate of each model after models were made shows that handmade model is the most successful model on designers' opinion. In this study, designers' expected judgement on choosing fabrication method to make the mini-flashlight model was wrong. 3D printed model didn't as successful as designers' expected. They met difficulties when they were making the model, such as the model taking too long to polish and the details not printing as expected. Designers didn't anticipate these problems before they built the model. On the other side, handmade model were smoothly made and the model looks the same as the original concept. Therefore, handmade model got the higher success rate than 3D printing model.

After twenty models were completed, designers are asked to rate the ease of making the model with the assigned fabrication method (Question#3 in late-survey). Different points were set for the choices, as shown in Table 6, and the average points of fabrication methods.

Table 6. Points for the choices (How easy)

Selection	Very Easy	Easy	General	Hard	Very Hard
Points(P)	4	3	2	1	0

Figure 37 lists the average scores for the relative difficulty of the fabrication methods. Making models with CNC is much more difficult than with the other two fabrication methods. The average score for CNC is 1.67, which means that the difficulty is between general and hard. According to feedback form participants, assemble the parts and polished them are very hard, even some participants have problems on printing the CNC model. Half of the 6 participants feel it was difficult for them to make the mini-flashlight model with CNC. For other 14 participants, making models with rapid prototyping and by hand were easy. The average scores for rapid prototyping and handmade modeling were 3.14 and 3.43 respectively. It means they didn’t meet too many difficulties when they were making the model. In general, participations made the model as their expectation. Compared with these two fabrication methods, handmade modeling is easier than with rapid prototyping. Because some participants thought polished the rapid prototyped model is difficult.

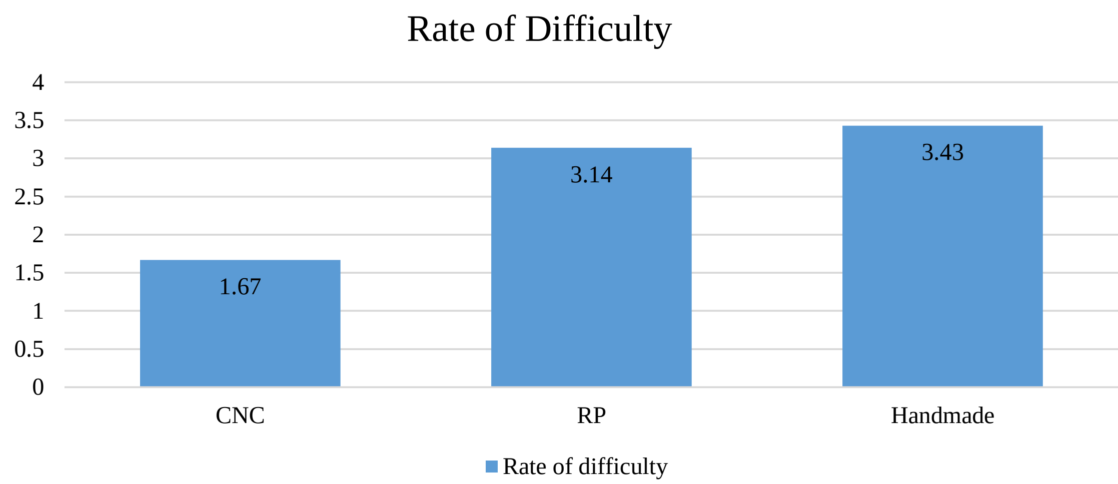


Figure 37. Rate of difficulty of making models with different fabrication methods

This experiment recorded the time spent on making the models. Table 11 lists the average time spent. Before the participants start making models, they choose the fabrication they want to use to make the mini-flashlight model. 7 participants think that making model with rapid prototyping is fast, so they choose this fabrication method. 5 participants say that handmade model needs less time. In consequence, the rank of the predicted speeds for these three fabrication methods is: rapid prototyping (fast) ＞ handmade modeling (neither fast nor slow) ＞computer numerical control (slow). However, the time records show a different result that handmade modeling costs less time. The average of time spent on making model is 8 hours, with 3 hours faster than other fabrication methods. The average of time spent on making model with rapid prototyping and CNC is 11.4 hours and 12.7 hours respectively.

Table 11. The average of time spent on making models

Speed	Fast	Neither Fast nor Slow	Slow
Prediction Speed	RP	Handmade	CNC
Time for Making Model	Handmade (8 hours)	RP (11.4 hours)	CNC (12.7 hours)

Handmade modeling is the best fabrication for making the mini-flashlight model among these three fabrication methods. Although more than half of the participants want to use rapid prototyping to make the model and think that the model would be very successful before they start making the models. After all the models have been made, handmade models get the highest successful rate, indicating that handmade modeling is the most efficient fabrication method costing the least time.

6.1.2 What factors influence designers in choosing a fabrication method?

Figure 38 shows the factors for designers to choose fabrication method. As shown in the figure, the complexity of the models and the speed of the fabrication method are the most important factors. More than half of the participants express that complexity and speed are their top priority. In this study, participants think that the mini-flashlight has some details, for the model is complicated. Therefore, most of them wanted to use rapid prototyping to make the model, which can build complicated models fast and easily.

The quantity and surface of the model will also influence designers to choose a fabrication method. There are five participants who want to make the model by hand, because they just need to build one model. One of the participants says that the flexibility of fabrication method is also an important factor for him to adjust the model timely.

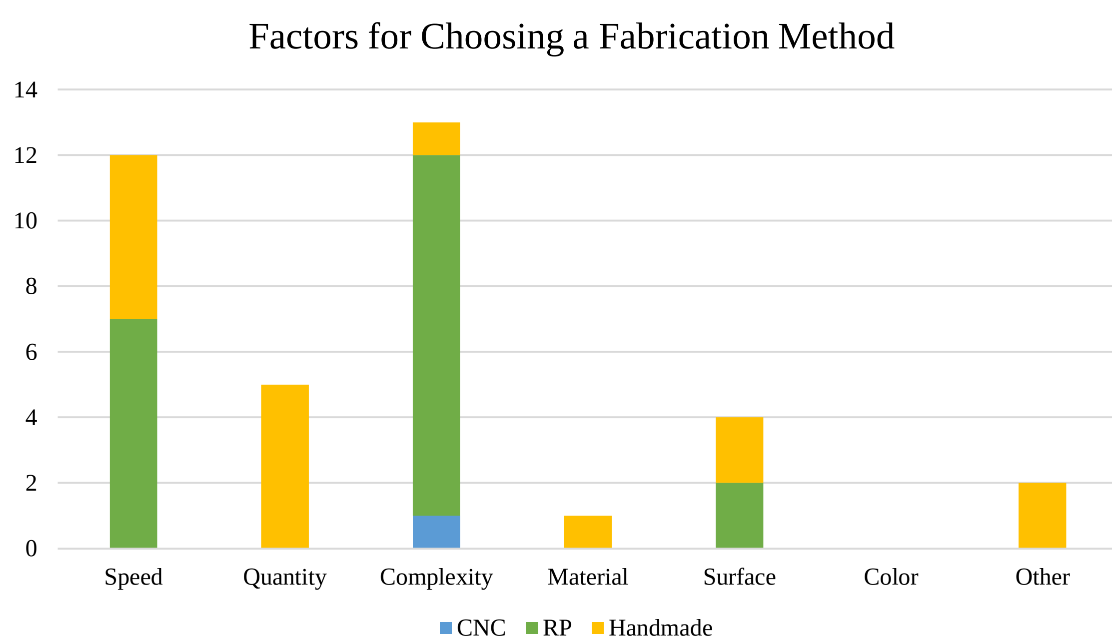


Figure 38. Factors for choosing a fabrication method

6.1.3 What type of models created using different fabrication methods is favored by the users?

According to the detailed information above, rapid prototyping is the best fabrication method for making mini-flashlight model among these three fabrication methods. However, this conclusion is from the perspective of the designers. From another perspective, what type of models do the users like most? The conclusion is achieved by collecting 200 evaluation investigations.

Figure 39 shows the average score of different factors. The evaluators think that the function of the laser-cut models is the best, as the average score is 4.22. Because most users know how to use the product easily and the lighting function was showed very well on the laser cut model. They thought the laser cut model's sizes are as good as handmade models. Nevertheless, as the sharp edges may hurt users' hand, laser-cut models get a very low score for its shape, which is 3.38. Handmade models get the highest score in terms of most aspects, such as size, shape, texture and material, which are 4.19, 4.17, 4.13 and 3.99. They thought these four aspects of the model match the description very well and they like the size and shape of the model. Even the scores of 3D-printed models are close to handmade models' score in terms of shape, texture and material. In consideration of all the aspects, handmade models are still the users' favorite model.

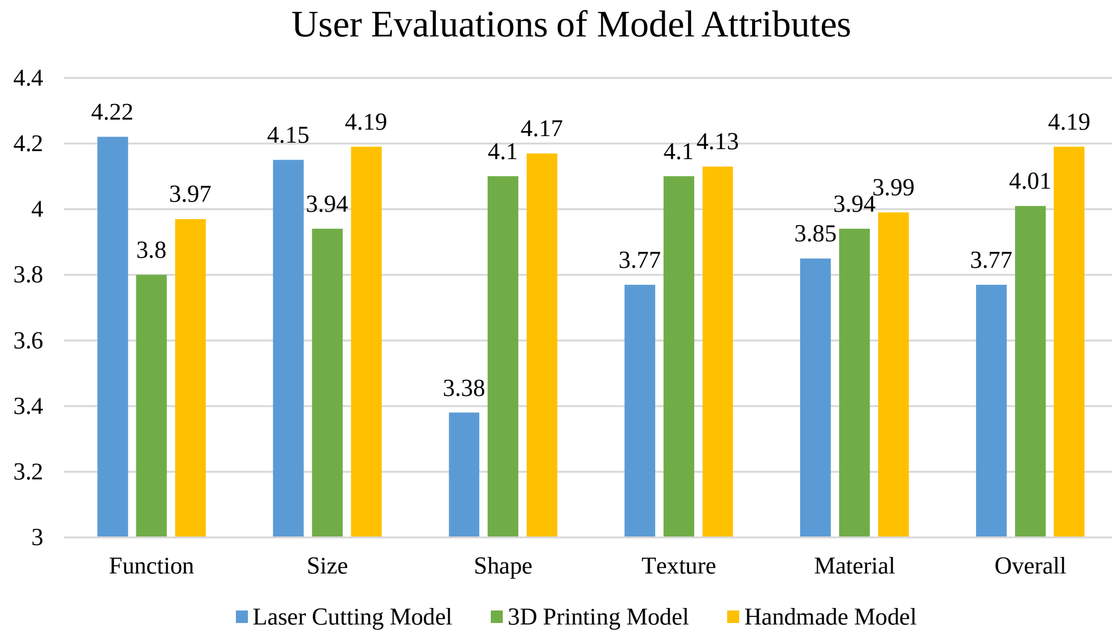


Figure 39. User evaluation of model attributes

For the refinement and appearance of the models, 3D-printed models get the highest score. As shown in figure 40, evaluators do not like the appearance of laser-cut models at all, and they think that the models are unrefined. The average scores of the refinement of 3D-printed models and handmade models are close, i.e. 4.13 and 4.01 respectively, which means that those models are refined. Only the average score of 3D-printed models' appearance is above 4, which shows that appearance of 3D-printed models is successful.

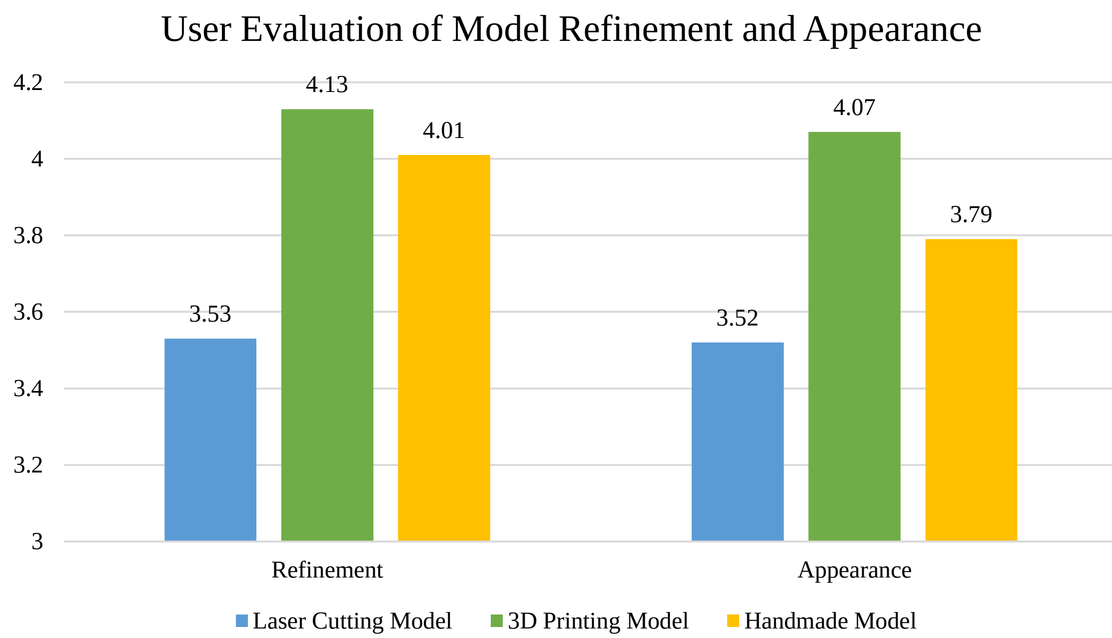


Figure 40. User evaluation of model refinement and appearance

Subsequently, the usages of models are evaluated. The evaluators are asked answer whether they know how to use the product by looking at this model; whether the product is easy to use and whether they think the product is useful. The result is shown in figure 41. Laser-cut models get the highest scores for these three questions, which are 4.58, 4.75 and 4.4. The evaluators express that they can know entirely how to use the product by looking at the laser-cut model, as the average is close to 5. The laser cut model looks like very easy to use, as the average is 4.75. Users can exactly know where is the button, how to turn it on/off. The average of usefulness of laser cut model is 4.4, meaning users thought the product is very useful by looking at the mini-flashlight model. However, a few evaluators want to buy the product by looking at laser-cut model. 3D-printed models made the evaluators confused on how to use it, as it got the lowest average score (4.4) on this question. Some evaluators said they cannot find the button. Some evaluators said they found the button, but they don’t know how to turn it on. Nevertheless, more evaluators want to buy it. The scores of handmade models are a little lower than laser-cut models in terms of usage.

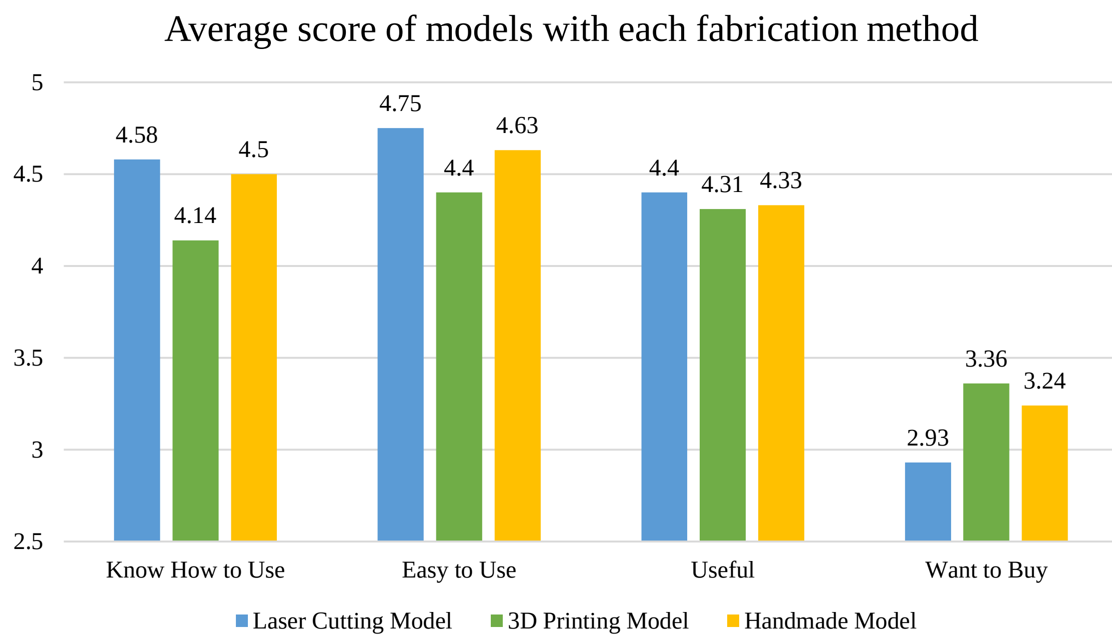


Figure 41. Average score of models with each fabrication method

Handmade models are most favored by the users, as they have got the highest scores for most aspects. The refinement and appearance of handmade models are accepted. Handmade models' average score of these two selections is closer to the average of 3D-print model. In addition, according to the feedbacks from 40 evaluators, handmade models make it very easy for the users to figure out how to use them, and they are very useful as well.

6.2 Comparisons

Designers and users gave the feedback according to their own requirements and experiences. The following comparison revealed some of the underlying reasons for the result of the surveys.

6.2.1 Designers' opinion and evaluators' opinion on the result model

Designers' opinion on the result model including many factors, which influence on designer to rate the successful of the model. Their opinion were not only for the result model itself, but also the process of making the model. In simpler terms, designers' success rate of the model was based on how difficult for them to make the model; how the model achieve the concept; whether the model was made as desired and so on. On the other side, users didn't know the manufacturing process of the model. They didn't know the original concept; whether the model was made as desired concept; how difficult to make the model. The only judge is the model itself.

For example, designers gave a very low success score for laser cut model. Because designers have a lot of problems when there are making the model, such as the model is too complex to build; it cost a lot of time to make the model; it's hard to assemble the model and process the finish surface. The fabrication method is too difficult for them to make the mini-flashlight model as desired concept. However, users thought the function and size of the laser cut model is the best. In addition, they could know how to use the product very well by looking at the model. They felt the product is the most useful and the easiest for them to use.

In this study, the designers' perception on the resulting model focus on the process of making the mode and how the model achieve the concept. Users only think about the model, not the process behind the model. If designers think more about the users' perception when they choose the fabrication method for making the model, they may get different scores for their models.

6.2.2 Designers' expectations and actual results

Designers expect to take the shortest time to build a model to show their concept perfectly. It is the reason that most designers chose 3D printing to build the model. Compare with laser cutting and handmade model making, designers don't need to care about how to make the details in physical. On their opinion 3D printing can complete a complex model fast. All the details can be showed on the model easily. Therefore, when they designed the mini-flashlight model, they added a lot of details on the model, such as model#3, model#8, model #14, model#18 and model#20. Certainly, 3D printed model got the highest score of the refinement and appearance of the model, which means users thought the 3D printed model is very refine and they like the appearance of the model. In this respect, designers' expectations were desired. However, the actually results is 3D printed models made users confused on using it, such as where is the button and how to turn it on.

The final result of the model included many aspects, which exceeded users' expectation. Designers expect their model can show their design perfectly and users will like their model. However, the using experience are also influence the actually result of the model. If designers consider this point when they are making the model, 3D printed model may got different result.

CHAPTER 7

CONCLUSION

The construction of models is an indispensable component in the innovation and final production phase of a design project. The objective of this paper was to figure out the relation between fabrication method and design outcome by focusing on these questions: Which fabrication method is the best choice for one type of model? What factors will influence designers' choice about fabrication method? What type of models, that making by different fabrication methods, are users' favorites? The fabrication methods include 3D Printing, Laser Cutting and Handmade Modeling.

Not surprisingly, most participants in model creation choose to use 3D printing to formulate the mini-flashlight appearance model and their expectations are very high. However, handmade models get the best feedback from 40 evaluators, showing that there is some common potential misconception in designers' mind. The fabrication method they want to choose does not necessarily lead to the best design outcome. Therefore, how to choose the best fabrication method has become a significant subject.

7.1 Significance of the study

This study has implications for designers in choosing the suitable fabrication method to make model. In general, most designers choose a fabrication method according to their own experience. Therefore, they will choose the acquainted fabrication method which they believe will result in a better design outcome. As a matter of fact, this study shows that the fabrication method that most designers want to use might not be the best choice.

For example, the mini-flashlight model is an appearance model, which means how the model looks is an important aspect to be considered. In addition, the model has some complicated details. Most participants chose 3D printing, as they believe it is convenient and efficient for them to make the model. However, in fact, it takes lots of time to develop the digital model and then reprocess it as the physical model. As we know, time is a critical and limited resource for any design project. Spending less time to get the best outcome is what designers are always looking for. In this regard, handmade model making is a better choice for making mini-flashlight model. There is no doubt that 3D printing model gets the highest score on refinement and appearance, due to the precise details and excellence to represent design. Nevertheless, handmade models tends to get as close a score on these two aspects and has higher ratings in other aspects. All in all, a handmade model will still lead to a better design outcome for making the mini-flashlight model in this study.

In addition, this study shows that there have difference opinions of the model between designers and users in judging the model. Users evaluate the model base on the model itself and designers have their subjective judgement. The original concept and the process of making the model will influence them to rate the model. However, designers create new product for users, which means users' opinions are the judgment criteria. After the model was made, designers have to pay most attentions on the model itself.

From this study, designers got an example that the fabrication method that most designers want to use didn't lead to the best result. And the opinions of the result model are different between designers and users. Therefore, when designer choose a fabrication method, they need to consider more about the type of the model, their concept and the users' opinions of the result model before they make it. Instead of choosing a fabrication method only base on designer's experience or their proficiency of the fabrication method.

This study points to a need for research in choosing an appropriate fabrication method in different design stages. As there is a common potential misconception of choosing a suitable fabrication method, comprehensive research of this topic will provide an invaluable reference for designers to choose an appropriate fabrication, which will manufacture a better product.

7.2 Limitation of the study

The limitation of this study is the sample size. The sample included three groups: participants, design stages (different types of model) and fabrication methods.

Most participants were from Georgia Institute of Technology. Despite more than three years' experience in industrial design, they choose to take similar courses which lead to the same acquainted fabrication method. Therefore, their choices of fabrication methods may be similar to formulate mini-flashlight model. The participants in this study may also have similar proficiency of fabrication methods which may influence the results.

As mentioned in chapter 2, there are different design stages in an industrial design project. Different types of model can help designers adjust their design in different design stages. In order to get an accurate result within limited time, this study only chooses the appearance model for manufacturing and evaluation. There are other types of models which have not been included in this study.

Due to resource constraints, all models in this study were made by three fabrication methods which are laser cutting, 3D printing and handmade modeling. To ensure the quality of the models, choosing these three fabrication methods are according to the result of related work. It shows that a majority of the participants choose to use these fabrication methods in their design project. However, there are a lot of fabrication methods which still need to be included.

In spite of its limitation, the result of this study is a great start as it points out the problems that designers really need to consider in choosing the fabrication method in different design stages.

7.3 Future Extension

Greater diversity in design participants would be needed. The participants, who have different experience in industrial design, will be invited in the future study. Other fabrication methods should be studied. Also different kinds of products would probably need to be investigated. Through collecting opinions from more designers, more experiments will be conducted to test different types of models. Thus, designer will get a comprehensive reference in choosing an appropriate fabrication method in different design stages. In future study, fabrication methods will not include only three models (Laser Cutting, 3D Printing and Handmade Modeling). Those widely used fabrication methods will be included as well. If possible, all the fabrication methods are expected to include.

In conclusion, this study is just a beginning for collecting the data about how to choose an appropriate fabrication method in different design stages. The further study still has a long way to go. Furthermore, the results of this study will definitely become a significant reference for designers.

APPENDIX A

PRE-SURVEY

Pre-Survey

Fabrication Method for Appearance Model

Designer Account #________

1. What fabrication method do you want to use for making your model in this study?

    Computer Numerical Control (included laser cutting, milling, water jet cutting)

    Rapid Prototyping (include 3D printing, stereo lithography, fused-deposition modeling)

    Injection Molding

    Handmade Model Making (include hand tools and conventional machines)

    Other_________________________

2. Why did you choose this fabrication method to make your model? (Multiple choice)

    Speed

    Quantity of components

    Complexity

    Material Choice

    Surface Finish

    Color

    Other_______________________

3. Rate how successful the final model will be by using this fabrication method:

Very successful	Successful	General	Unsuccessful	Very unsuccessful
☐	☐	☐	☐	☐

4. What fabrication method you are assigned?

    Computer Numerical Control (included laser cutting, milling, water jet cutting)

Rapid Prototyping (include 3D printing, stereo lithography, fused-deposition modeling)

Handmade Model Making (include hand tools and conventional machines)

5. Rate how successful the final model will be by using your assigned fabrication method:

Very successful	Successful	General	Unsuccessful	Very unsuccessful
☐	☐	☐	☐	☐

6. What do you want to change about the concept to make it work better with the assigned method? Why?

APPENDIX B

LATE-SURVEY

Late-Survey

Fabrication Method for Making Model

Designer Account #________

1. What fabrication method you are assigned?

    Computer Numerical Control (included laser cutting, milling, water jet cutting)

    Rapid Prototyping (include 3D printing, stereo lithography, fused-deposition modeling)

    Handmade Model Making (include hand tools and conventional machines)

2. Rate how successful the final model is by using your assigned fabrication method:

Very successful	Successful	General	Unsuccessful	Very unsuccessful
☐	☐	☐	☐	☐

3. Rate how easy to make the model by using your assigned fabrication?

Very Easy	Easy	General	Hard	Very Hard
☐	☐	☐	☐	☐

4. What’s the difficult factor for using your assigned fabrication to make model? (Multiple choice)

    Speed

    Quantity of components

    Complexity

    Material Choice

    Surface Finish

    Color

    Other______________________

5. What problems did you face while making the model? How did you solve the problems?

____

____

____

6. What do you want to change about the concept to make it work better with the assigned method? Why?

____

____

APPENDIX C

EVALUATION-SURVEY

Evaluation-Survey

Fabrication Method for Making the Model

Evaluator Account #________ Model Number #________

1. Rate the model on a scale of 1 to 5, 5 meaning that the model meets the description in all aspects of this study:

	1	2	3	4	5
Function					
Size					
Shape					
Texture					
Material					
Overall					

2. Is the model refined? (Rate the model 1 to 5, 5 meaning that the model is refined.)

1	2	3	4	5

3. Do you like the model's appearance? (Rate the model 1 to 5, 5 meaning that you like the mode's appearance very much.)

1	2	3	4	5

4. Do you know how to use the product by look at this model? (Rate the model 1 to 5, 5

1	2	3	4	5

5. Is the product easy to use? (Rate the model 1 to 5, 5 meaning that the product is very easy to use.)

1	2	3	4	5

6. Do you think the product is useful? (Rate the model 1 to 5, 5 meaning that the product is very useful.)

1	2	3	4	5

7. Do you want to buy this product? (Rate the model 1 to 5, 5 meaning that you really want to buy this product.)

1	2	3	4	5

8. What do you wish to change or improve upon the model?

____

____

APPENDIX D

CONCEPT DESCRIPTION

Concept Description

Product Name: Mini-Flashlight

Function: Portable Lighting

Size：4” x1.5” X1.5” Inch

Color: Black and Yellow

Shape: Cylinder or Cuboid

Texture: Smooth

Material: Glass and Plastics

APPENDIX E

SURVEYS IN RELATE WORK

Subject Number____________________

Use of Digital Fabrication by Industrial Design Students
Early Project Survey

1) Please circle the current studio that you are taking:

Sophomore Junior Senior Graduate

2) Please indicate the fabrication method(s) that you utilized to create models during the early ideation phase of your most recent studio project.

Place an X next to any fabrication method you used in the ideation phase of your project.

Fabrication Method	**Place an X**
3-D Printing	
Laser Cutting	
Vacuum Molding	
Tools to work with: Pink Foam/High Density Foam/Wood	
Other	

Please list each model fabrication method that you used in your project not listed in the above table.

3) For each method that you used, please briefly explain the reasons that you chose to utilize it in the early phase of your particular project. What benefit do you expect to gain from using each method?

Subject Number_________________

Use of Digital Fabrication by Industrial Design Students
Late Project Survey

1) Please circle the current studio that you are taking:

Sophomore Junior Senior Graduate

2) Please indicate the fabrication method(s) that you utilized to create the final models at the end of your most recent studio project.

Place an X next to any fabrication method you used to create the final model in your project.

Fabrication Method	**Place an X**
3-D Printing	
Laser Cutting	
Vacuum Molding	
Tools to work with: Pink Foam/High Density Foam/Wood	
Other	

Please list each model fabrication method that you used in your project not listed in the above table.

3) For each method that you used, please briefly explain the reasons that you chose to utilize it to produce the final models for your particular project. What benefit did you expect to gain from using each method?

4) Please indicate how successful you feel that the model fabrication methods you utilized in the **EARLY** stages of your project met your expectations.

Place an X next to your opinion of how successful the fabrication methods you used in the EARLY phase of your project were. If you used a method that is not listed, please fill it in under the Fabrication Method and rank how successful it was in your project.

Fabrication Method	Highly Successful (5)	Somewhat Successful (4)	Neither successful nor unsuccessful (3)	Somewhat Unsuccessful (2)	Very Unsuccessful (1)
3-D Printing					
Laser Cutting					
Vacuum Molding					
Tools to work with: Pink Foam/High Density Foam/Wood					

5) Please indicate how successful you feel that the model fabrication methods you utilized in the **FINAL** stages of your project met your expectations.

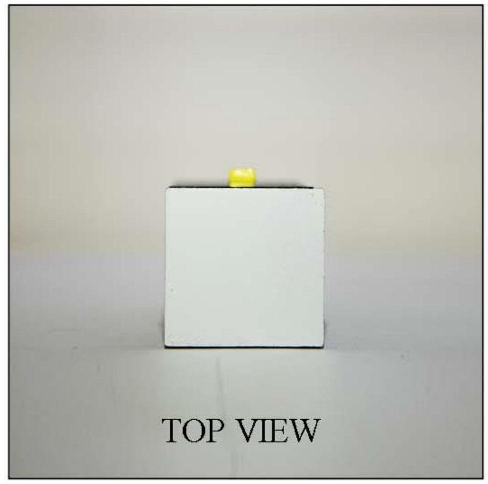
Place an X next to your opinion of how successful the fabrication methods you used in the FINAL phase of your project were. If you used a method that is not listed, please fill it in under the Fabrication Method and rank how successful it was in your project.

Fabrication Method	Highly Successful (5)	Somewhat Successful (4)	Neither successful nor unsuccessful (3)	Somewhat Unsuccessful (2)	Very Unsuccessful (1)
3-D Printing					
Laser Cutting					
Vacuum Molding					
Tools to work with: Pink Foam/High Density Foam/Wood					

APPENDIX F

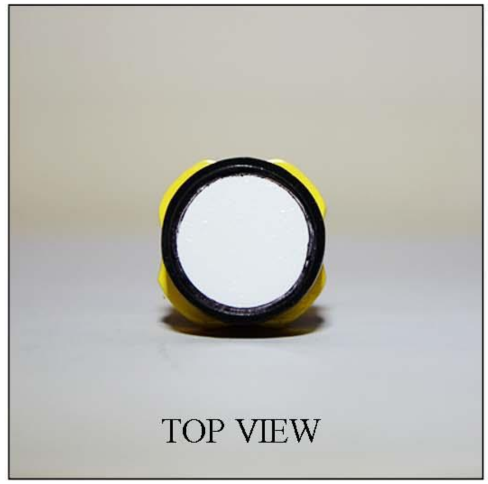
MODELS IN THIS STUDY

MODEL#1



<table>
<tr><td colspan="2">Fabrication Method:</td><td>Function</td><td>3.8</td><td>Refinement</td><td>3.2</td></tr>
<tr><td colspan="2">Laser Cutting</td><td>Size</td><td>3.3</td><td>Appearence</td><td>2.6</td></tr>
<tr><td>Production Time:</td><td>8 hours</td><td>Shape</td><td>2.6</td><td>Know How to Use</td><td>4.3</td></tr>
<tr><td colspan="2" rowspan="3">*The scores in this table are the averages of the model's rating from 10 evaluators.</td><td>Texture</td><td>3.8</td><td>Easy to Use</td><td>4.6</td></tr>
<tr><td>Material</td><td>3.7</td><td>Useful Rate</td><td>4.1</td></tr>
<tr><td>Overall</td><td>3.4</td><td>Want to Buy</td><td>2.5</td></tr>
</table>

MODEL#2



Fabrication Method:		Function	4.3	Refinement	3.6
Laser Cutting		Size	4.1	Appearence	3.8
Production Time:	20 hours	Shape	3.4	Know How to Use	3.7
*The scores in this table are the averages of the model's rating from 10 evaluators.		Texture	4.0	Easy to Use	4.1
		Material	4.0	Useful Rate	4.5
		Overall	3.8	Want to Buy	3.2

MODEL#3


PERSPECTIVE VIEW


TOP VIEW

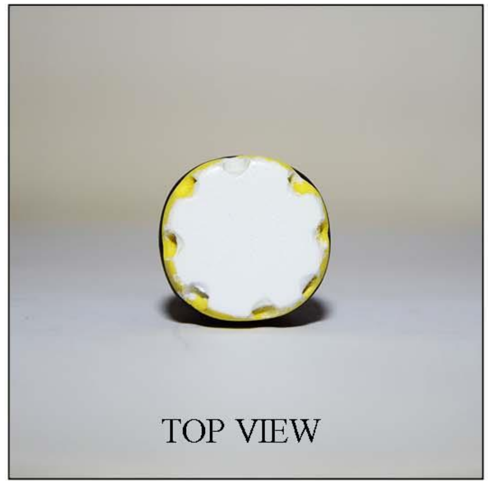

LEFT SIDE VIEW


FRONT VIEW

Fabrication Method:		Function	4.0	Refinement	4.4
3D Printing		Size	4.6	Appearence	4.6
Production Time:	11 hours	Shape	4.7	Know How to Use	4.9
*The scores in this table are the averages of the model's rating from 10 evaluators.		Texture	4.3	Easy to Use	4.9
		Material	4.1	Useful Rate	4.6
		Overall	4.5	Want to Buy	4.0

MODEL#4


PERSPECTIVE VIEW


TOP VIEW


LEFT SIDE VIEW


FRONT VIEW

<table>
<tr><td colspan="2">Fabrication Method:</td><td>Function</td><td>3.8</td><td>Refinement</td><td>4.1</td></tr>
<tr><td colspan="2">Handmade Modeling</td><td>Size</td><td>4.1</td><td>Appearence</td><td>3.5</td></tr>
<tr><td>Production Time:</td><td>7 hours</td><td>Shape</td><td>4.3</td><td>Know How to Use</td><td>4.1</td></tr>
<tr><td colspan="2" rowspan="3">*The scores in this table are the averages of the model's rating from 10 evaluators.</td><td>Texture</td><td>4.2</td><td>Easy to Use</td><td>4.4</td></tr>
<tr><td>Material</td><td>4.1</td><td>Useful Rate</td><td>3.8</td></tr>
<tr><td>Overall</td><td>4.2</td><td>Want to Buy</td><td>3.0</td></tr>
</table>

MODEL#5

PERSPECTIVE VIEW

TOP VIEW

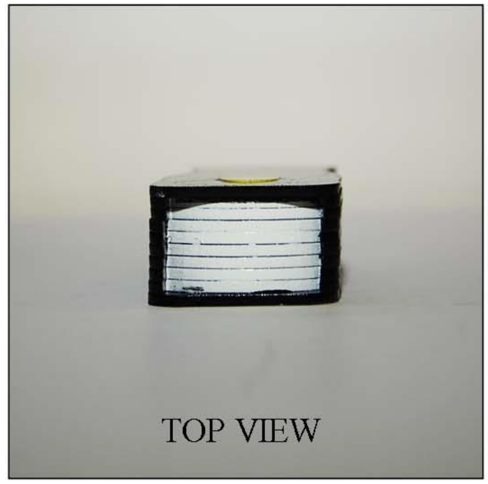
LEFT SIDE VIEW

FRONT VIEW

Fabrication Method:		Function	3.2	Refinement	3.9
Handmade Modeling		Size	4.8	Appearence	3.7
Production Time:	6 hours	Shape	3.9	Know How to Use	3.2
*The scores in this table are the averages of the model's rating from 10 evaluators.		Texture	3.9	Easy to Use	3.5
		Material	3.7	Useful Rate	4.2
		Overall	3.7	Want to Buy	2.7

MODEL#6


PERSPECTIVE VIEW

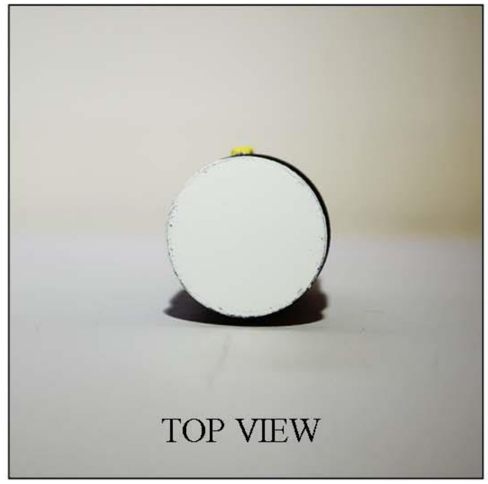

TOP VIEW


LEFT SIDE VIEW


FRONT VIEW

Fabrication Method:		Function	4.3	Refinement	4.0
Laser Cutting		Size	4.6	Appearence	3.8
Production Time:	7 hours	Shape	3.9	Know How to Use	5.0
*The scores in this table are the averages of the model's rating from 10 evaluators.		Texture	3.8	Easy to Use	5.0
		Material	4.0	Useful Rate	4.4
		Overall	4.1	Want to Buy	3.0

MODEL#7



Fabrication Method:		Function	3.5	Refinement	3.6
3D Printing		Size	3.5	Appearence	3.9
Production Time:	9 hours	Shape	3.1	Know How to Use	4.2
*The scores in this table are the averages of the model's rating from 10 evaluators.		Texture	3.8	Easy to Use	4.6
		Material	3.8	Useful Rate	4.4
		Overall	3.7	Want to Buy	3.2

MODEL#8

PERSPECTIVE VIEW

TOP VIEW

LEFT SIDE VIEW

FRONT VIEW

Fabrication Method:		Function	3.9	Refinement	4.1
3D Printing		Size	3.9	Appearence	4.3
Production Time:	18 hours	Shape	4.5	Know How to Use	4.9
*The scores in this table are the averages of the model's rating from 10 evaluators.		Texture	4.3	Easy to Use	4.7
		Material	3.9	Useful Rate	4.2
		Overall	4.0	Want to Buy	3.6

MODEL#9

Fabrication Method:		Function	4.0	Refinement	4.1
3D Printing		Size	3.4	Appearence	4.0
Production Time:	10 hours	Shape	4.6	Know How to Use	5.0
*The scores in this table are the averages of the model's rating from 10 evaluators.		Texture	4.2	Easy to Use	5.0
		Material	4.0	Useful Rate	4.4
		Overall	3.8	Want to Buy	3.3

MODEL#10


PERSPECTIVE VIEW

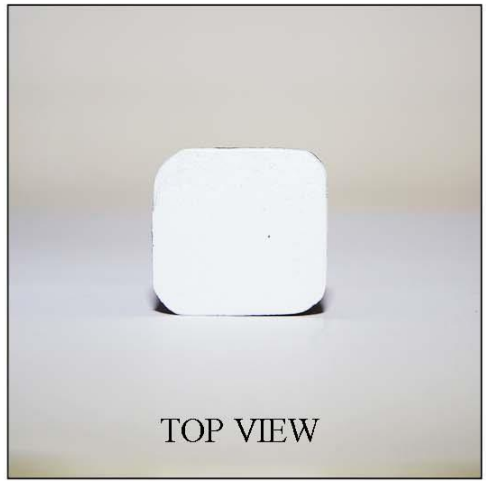

TOP VIEW

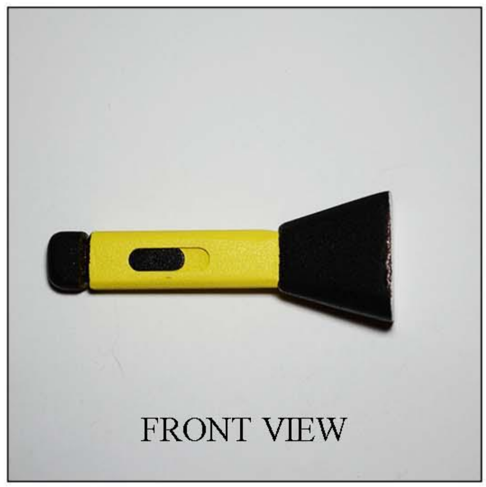

LEFT SIDE VIEW


FRONT VIEW

Fabrication Method:		Function	4.6	Refinement	3.2
Laser Cutting		Size	4.6	Appearence	3.3
Production Time:	10 hours	Shape	3.3	Know How to Use	5.0
*The scores in this table are the averages of the model's rating from 10 evaluators.		Texture	3.4	Easy to Use	5.0
		Material	3.6	Useful Rate	4.5
		Overall	3.8	Want to Buy	2.8

MODEL#11

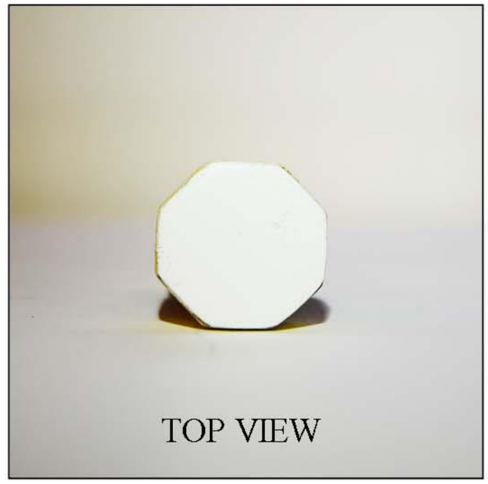




Fabrication Method:		Function	4.2	Refinement	4.1
Handmade Modeling		Size	4.6	Appearence	4.0
Production Time:	8 hours	Shape	4.0	Know How to Use	5.0
*The scores in this table are the averages of the model's rating from 10 evaluators.		Texture	4.4	Easy to Use	5.0
		Material	4.5	Useful Rate	4.8
		Overall	4.4	Want to Buy	3.7

MODEL#12


PERSPECTIVE VIEW


TOP VIEW

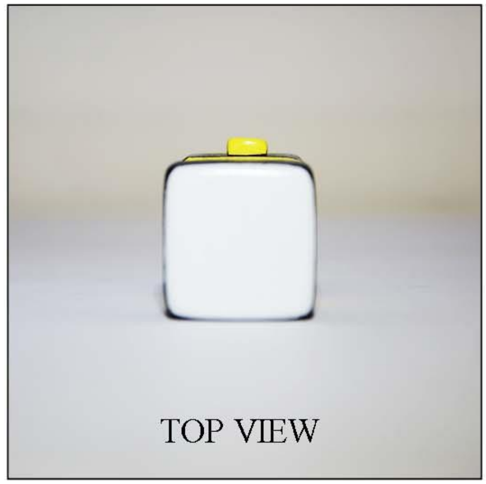

LEFT SIDE VIEW


FRONT VIEW

Fabrication Method:		Function	4.5	Refinement	4.6
Handmade Modeling		Size	4.0	Appearence	4.2
Production Time:	12 hours	Shape	4.6	Know How to Use	5.0
*The scores in this table are the averages of the model's rating from 10 evaluators.		Texture	4.7	Easy to Use	5.0
		Material	4.4	Useful Rate	4.4
		Overall	4.7	Want to Buy	3.8

MODEL#13

PERSPECTIVE VIEW



TOP VIEW

LEFT SIDE VIEW

FRONT VIEW

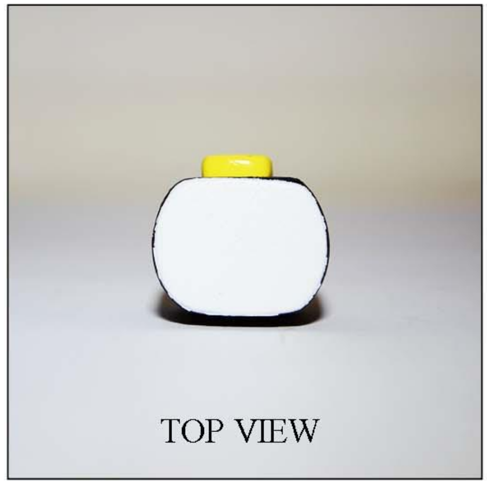
Fabrication Method:		Function	4.0	Refinement	3.2
Handmade Modeling		Size	3.5	Appearence	3.4
Production Time:	6 hours	Shape	3.7	Know How to Use	4.6
*The scores in this table are the averages of the model's rating from 10 evaluators.		Texture	3.7	Easy to Use	4.6
		Material	3.5	Useful Rate	4.1
		Overall	3.8	Want to Buy	2.8

MODEL#14

Fabrication Method:		Function	4.0	Refinement	4.1
3D Printing		Size	4.1	Appearence	4.0
Production Time:	9 hours	Shape	3.9	Know How to Use	3.9
*The scores in this table are the averages of the model's rating from 10 evaluators.		Texture	3.8	Easy to Use	4.5
		Material	3.8	Useful Rate	4.5
		Overall	4.1	Want to Buy	3.7

MODEL#15

PERSPECTIVE VIEW



TOP VIEW

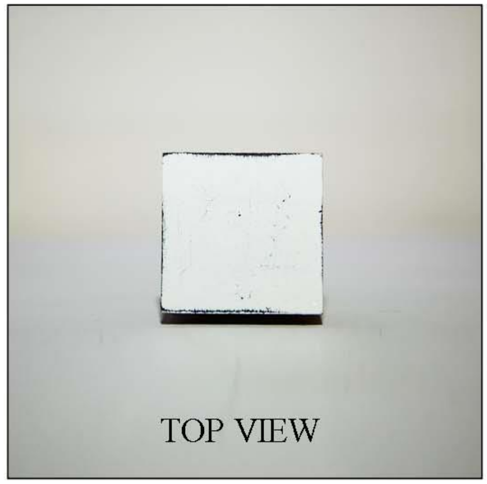
LEFT SIDE VIEW

FRONT VIEW

Fabrication Method:		Function	3.9	Refinement	3.9
Handmade Modeling		Size	4.1	Appearence	3.7
Production Time:	9 hours	Shape	4.0	Know How to Use	4.8
*The scores in this table are the averages of the model's rating from 10 evaluators.		Texture	3.8	Easy to Use	5.0
		Material	3.4	Useful Rate	4.3
		Overall	4.0	Want to Buy	3.3

MODEL#16

PERSPECTIVE VIEW



TOP VIEW

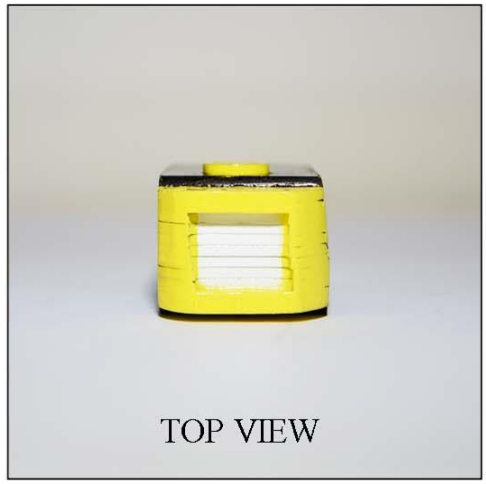
LEFT SIDE VIEW

FRONT VIEW

Fabrication Method:		Function	3.8	Refinement	3.4
Laser Cutting		Size	4.0	Appearence	3.5
Production Time:	16 hours	Shape	3.3	Know How to Use	4.7
*The scores in this table are the averages of the model's rating from 10 evaluators.		Texture	3.7	Easy to Use	4.8
		Material	3.8	Useful Rate	4.5
		Overall	3.6	Want to Buy	3.0

MODEL#17

PERSPECTIVE VIEW



TOP VIEW

LEFT SIDE VIEW

FRONT VIEW

Fabrication Method:		Function	4.5	Refinement	3.8
Laser Cutting		Size	4.3	Appearence	4.1
Production Time:	15 hours	Shape	3.8	Know How to Use	4.8
*The scores in this table are the averages of the model's rating from 10 evaluators.		Texture	3.9	Easy to Use	5.0
		Material	4.0	Useful Rate	4.4
		Overall	3.9	Want to Buy	3.1

MODEL#18

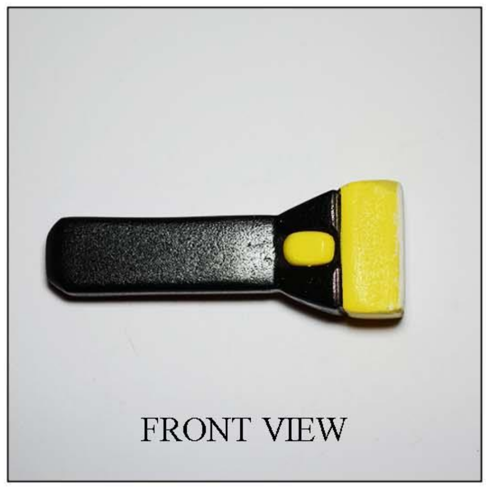
Fabrication Method:		Function	3.9	Refinement	4.5
3D Printing		Size	4.2	Appearence	3.9
Production Time:	11 hours	Shape	4.0	Know How to Use	2.8
*The scores in this table are the averages of the model's rating from 10 evaluators.		Texture	3.9	Easy to Use	3.5
		Material	3.9	Useful Rate	4.0
		Overall	4.1	Want to Buy	2.9

MODEL#19


PERSPECTIVE VIEW


TOP VIEW


LEFT SIDE VIEW


FRONT VIEW

Fabrication Method:		Function	4.2	Refinement	4.3
Handmade Modeling		Size	4.2	Appearence	4.0
Production Time:	8 hours	Shape	4.7	Know How to Use	4.8
*The scores in this table are the averages of the model's rating from 10 evaluators.		Texture	4.2	Easy to Use	4.9
		Material	4.3	Useful Rate	4.7
		Overall	4.5	Want to Buy	3.9

MODEL#20

PERSPECTIVE VIEW

TOP VIEW

LEFT SIDE VIEW

FRONT VIEW

Fabrication Method:		Function	3.3	Refinement	4.1
3D Printing		Size	3.9	Appearence	3.8
Production Time:	12 hours	Shape	3.9	Know How to Use	3.3
*The scores in this table are the averages of the model's rating from 10 evaluators.		Texture	4.4	Easy to Use	3.6
		Material	4.1	Useful Rate	4.1
		Overall	3.9	Want to Buy	2.8

APPENDIX G

IRB CONSENT FORM

CONSENT DOCUMENT FOR ENROLLING ADULT PARTICIPANTS IN A RESEARCH STUDY

Georgia Institute of Technology
Project Title:
Investigators: *Dr. Young Mi Choi, Linye Zhang*

Protocol and Consent Title: *A study of Fabrication Methods and Design Outcome - Design*

You are being asked to be a volunteer in a research study.

Purpose:
The purpose of this study is to investigate the relation between the fabrication methods used for model construction during the design process and the perceived success of the final design outcome. The construction of models is an important component in the innovation and final production phase of a design project. They are the key to testing concept to identify and correct design or usability problems. Models at each stage of the design process accurately represent the concept and so it is important to choose fabrication methods that are appropriate for the goals of the model. The fabrication methods in this study included Computer Numerical Control, 3D printing and handmade molding. We expect to enroll 20 people in this study.

Exclusion/Inclusion Criteria:
Participants in this study must be:

- over the age of eighteen
- A current undergraduate or graduate industrial design student.

Procedures:
You will be randomly (by chance, like flipping a coin) assigned to build a model using one of the fabrication methods being investigated in this study (Computer Numerical Control, 3D printing and handmade molding).

There will be weekly visits to collect data through the course of the study.

- The initial visit will take approximately three hours. In it you will get a description of the product to be designed, the fabrication method that you will use and complete a questionnaire about how/why you normally choose a particular fabrication method.

- You will work on the model five to ten hours per week for the following four weeks. During these weekly data collection visits, you will be asked to show your model and describe the design/fabrication process. Pictures of your model will be taken. These visits will take no more than one hour.
- The final data collection visit will take approximately three hours. During this visit, you will be asked for hand in your model and answer some questions about it.

The total amount of time you will spend in this study should be no more than fifty hours.

We will provide all the materials for making models.

Risks or Discomforts:
The only risks that may occur during this study are related to the use of machines and tools to make the models. As ID students participants should be aware of potential risks, which are not greater than encountered during normal ID project course work.

Benefits:
You are not likely to benefit in any way from joining this study. We hope that what we learn will someday help others with choose an appropriate method to build models in their project.

Compensation to You:
There is no compensation for participation.

Confidentiality:
The following procedures will be followed to keep your personal information confidential in this study: The data collected about you will be kept private to the extent allowed by law. To protect your privacy, your records will be kept under a code number rather than by name. Your records will be kept in locked files and only study staff will be allowed to look at them. Your name and any other fact that might point to you will not appear when results of this study are presented or published. Your privacy will be protected to the extent allowed by law. To make sure that this research is being carried out in the proper way, the Georgia Institute of Technology IRB may review study records. The Office of Human Research Protections may also look over study records during required reviews.

Costs to You:

There are no costs to you, other than your time, for being in this study.

In Case of Injury/Harm:
If you are injured as a result of being in this study, please contact Linye Zhang, at telephone (404) 951-6720. Neither the Principal Investigator nor Georgia Institute of Technology has made provision for payment of costs associated with any injury resulting from participation in this study.

Participant Rights:

- Your participation in this study is voluntary. You do not have to be in this study if you don't want to be.
- You have the right to change your mind and leave the study at any time without giving any reason and without penalty.
- Any new information that may make you change your mind about being in this study will be given to you.
- You will be given a copy of this consent form to keep.
- You do not waive any of your legal rights by signing this consent form.

Questions about the Study:
If you have any questions about the study, you may contact Dr. Young Mi Choi at telephone (404) 277-2748 or christina.choi@gatech.edu.

Questions about Your Rights as a Research Participant:
"If you have any questions about your rights as a research participant, you may contact

Ms. Melanie Clark, Georgia Institute of Technology
Office of Research Integrity Assurance, at (404) 894-6942."
[or]
"Ms. Kelly Winn, Georgia Institute of Technology
Office of Research Integrity Assurance, at (404) 385- 2175."

If you sign below, it means that you have read (or have had read to you) the information given in this consent form, and you would like to be a volunteer in this study.

____
Participant Name (printed)

____ ____________

Participant Signature Date

____________________________________ ______________
Signature of Person Obtaining Consent Date

CONSENT DOCUMENT FOR ENROLLING ADULT PARTICIPANTS IN A RESEARCH STUDY

Georgia Institute of Technology
Project Title:
Investigators: *Dr. Young Mi Choi, Linye Zhang*

Protocol and Consent Title: *A study of Fabrication Methods and Design Outcome- Evaluate*

You are being asked to be a volunteer in a research study.

Purpose:
The purpose of this study is to investigate the relation between the fabrication methods used for model construction during the design process and the perceived success of the final design outcome. The construction of models is an important component in the innovation and final production phase of a design project. They are the key to testing concept to identify and correct design or usability problems. Models at each stage of the design process accurately represent the concept and so it is important to choose fabrication methods that are appropriate for the goals of the model. The fabrication methods in this study included Computer Numerical Control, 3D printing and handmade molding. We expect to enroll 40 people in this study.

Exclusion/Inclusion Criteria:
Participants in this study must be over the age of eighteen and be able to provide consent to participate.

Procedures:

- You will be randomly (by chance, like flipping a coin) assigned a group model, which include five models.
- If you decide to be in this study, your part will involve participation in a single study session. During the study session, you will be shown five models that you will be evaluating. A description of the model will be read to you. After you get the description and observant the models carefully, you will be asked to complete a survey for each model that ask about your opinion about various aspects of the models that you were shown. The total amount of time you will spend in this study is no more than three hours.

Risks or Discomforts:

The risks involved are no greater than those involved in daily activities.

Benefits:
You are not likely to benefit in any way from joining this study. We hope that what we learn will someday help others with choose an appropriate method to build models in their project.

Compensation to You:
There is no compensation for participation.

Confidentiality:
The following procedures will be followed to keep your personal information confidential in this study: The data collected about you will be kept private to the extent allowed by law. To protect your privacy, your records will be kept under a code number rather than by name. Your records will be kept in locked files and only study staff will be allowed to look at them. Your name and any other fact that might point to you will not appear when results of this study are presented or published. Your privacy will be protected to the extent allowed by law. To make sure that this research is being carried out in the proper way, the Georgia Institute of Technology IRB may review study records. The Office of Human Research Protections may also look over study records during required reviews.

Costs to You:
There are no costs to you, other than your time, for being in this study.

In Case of Injury/Harm:
If you are injured as a result of being in this study, please contact Linye Zhang, at telephone (404) 951-6720. Neither the Principal Investigator nor Georgia Institute of Technology has made provision for payment of costs associated with any injury resulting from participation in this study.

Participant Rights:
- Your participation in this study is voluntary. You do not have to be in this study if you don't want to be.
- You have the right to change your mind and leave the study at any time without giving any reason and without penalty.
- Any new information that may make you change your mind about being in this study will be given to you.
- You will be given a copy of this consent form to keep.

- You do not waive any of your legal rights by signing this consent form.

Questions about the Study:
If you have any questions about the study, you may contact Dr. Young Mi Choi at telephone (404) 277-2748 or christina.choi@gatech.edu.

Questions about Your Rights as a Research Participant:
"If you have any questions about your rights as a research participant, you may contact

Ms. Melanie Clark, Georgia Institute of Technology
Office of Research Integrity Assurance, at (404) 894-6942."
[or]
"Ms. Kelly Winn, Georgia Institute of Technology
Office of Research Integrity Assurance, at (404) 385- 2175."

If you sign below, it means that you have read (or have had read to you) the information given in this consent form, and you would like to be a volunteer in this study.

____
Participant Name (printed)

____ ____________
Participant Signature Date

____ ____________
Signature of Person Obtaining Consent Date

REFERENCES

[1] ENTREPRENEUR “Prototype” (Oct. 2013) http://www.entrepreneur.com/article/80678

[2] VORELCO “Prototyping” (Oct. 2013) http://www.vorelco.com/services/prototyping

[3] PROTO LABS “Design Processes” (Oct.2013) http://www.protolabs.com/?awk=true “Choosing the best process for your project”

[4] Hitachi Software Engineering Co., L. d. (n.d). Hitachi Software Engineering Co., Ltd. Yuka Shoken 1997.

[5] Schatzberg, E. E. (1999). Henry Petroski, Invention by Design: How Engineers Get from Thought to Thing.

[6] Budde, R, Kautz, K and Kuhlenkamp, K (1992) Prototyping: an approach to evolutionary system development Springer, Berlin

[7] LEARDON “Prototype” (Oct. 2013) http://leardon.com/what-is-a-production-prototype

[8] Yang, M. C. (2005). A study of prototypes, design activity, and design outcome. Design Studies, 26(6), 649-669. doi:10.1016/j.destud.2005.04.005

[9] Wilson, D. W., Bailey, L. E., & Bennett, C. E. (2000). Expanding mechanical design and fabrication horizons. Johns Hopkins APL Technical Digest, 21(4), 506-515.

[10] Phillips Plastics Corporation, November. 2009, Choosing the Right Rapid Prototype Source for Your Product Development Program

[11] B. Asberg, G. Blanco, P. Bose, J. Garcia-Lopez, M. Overmars, G. Toussaint, G. Wilfong and B. Zhu, "Feasibility of design in stereolithography," Algorithmica, Special Issue on Computational Geometry in Manufacturing, Vol. 19, No. 1/2, Sept/Oct, 1997, pp. 61 – 83.

[12] Digital fabrication in the architectural design process. [serial online]. 2005;Available from: OAIster, Ipswich, MA. Accessed May 5, 2015.

[13] Prinz, F. B.; Merz, R.; Weiss, Lee (1997). Ikawa, N., ed. Building Parts You Could Not Build Before. Proceedings of the 8th International Conference on Production Engineering. 2-6 Boundary Row, London SE1 8HN, UK: Chapman & Hall. pp. 40–44.

[14] Perrottet, D et al.,"Heat damage-free Laser-Microjet cutting achieves highest die fracture strength", Photon Processing in Microelectronics and Photonics IV, edited by J. Fieret, et al., Proc. of SPIE Vol. 5713 (SPIE, Bellingham, WA, 2005)

[15] ROBERT Q.RILEY ENTERPRISES “product design” (Oct. 2013) http://www.rqriley.com/pro-dev.htm “Product Design & Development——The Generic Process for Developing New Products”

[16] Archer, L. (1974). Design awareness and planned creativity in industry.

[17] Cross, N. (2000). Engineering design methods [electronic resource] : strategies for product design / Nigel Cross. Chichester ; New York : Wiley, c2000.

[18] Kocabiyik, E. (2004) Engineering Concepts in Industrial Product Design With A Case Study of Bicycle Design

[19] ZURB UNIVERSITY “Design process” (Oct. 2013) http://zurb.com/word/design-process

[20] BOXES AND ARROWS “Design process” (Oct. 2013) http://boxesandarrows.com/integrating-prototyping-into-your-design-process/ Integrating Prototyping Into Your Design Process

[21] SCULPTEO “3D printing” (Oct. 2013) http://www.sculpteo.com/en/help/#object-maximum-size

[22] Evans, M., & Campbell, R. (2003). A comparative evaluation of industrial design models produced using rapid prototyping and workshop-based fabrication techniques. Rapid Prototyping Journal, 9(5), 344-351. doi:10.1108/13552540310502248

[23] Urban, Glen L. and Hauser, John R. Design and Marketing of New Products, 2nd Edition. Englewood Cliffs, NJ: Prentice-Hall, 1993.

[24] Ozer, M. (1999). A Survey of New Product Evaluation Models. Journal of Product Innovation Management, 16(1), 77-94.

[25] Stoll H. Product Design Methods And Practices [Electronic Resource] / Henry W. Stoll [e-book]. New York : Marcel Dekker, 1999.; 1999. Available from: GT Library Catalog, Ipswich, MA. Accessed May 5, 2015.

[26] The future role of virtual and physical modelling in industrial design. [serial online]. 1993;Available from: OAIster, Ipswich, MA. Accessed May 5, 2015.

[27] Tovey M. Design Pedagogy : Developments In Art And Design Education / [Compiled] By Mike Tovey [e-book]. Farnham, Surrey, UK England ; Burlington, VT, USA : Gower, [2015]; 2015. Available from: GT Library Catalog, Ipswich, MA. Accessed May 5, 2015.