RAPID PROTOTYPING AND ITS ROLE IN SUPPORTING ARCHITECTURAL DESIGN PROCESS

M.Sanem Bayar[1], Zeeshan Aziz[2]

ABSTRACT

Model making is a crucial part of the design development for evaluating the form, fit and functionality of a design before a notable investment is performed. The emergence of novel technologies and their increasing uptake are helping to redefine the architecture and the architects' master builder role, by altering the way architects think and make things. Different methods and strategies are available to utilize for production of artefacts that are considered not only to be new communication and representation tools but also being utilized for testing and evaluation during design processes. Rapid prototyping processes are forming a language between different phases of the design and considered as a feedback mechanism informing each other. This paper presents experimental research products of two rapid prototyping technologies, focusing on how each technology can effectively be used in the delivery of design intent. Prototyping machines were used in testing the accuracy of the geometry of the design, in terms of protecting the design intent within the production process of each model. In order to verify the results of the experiment, researchers conducted semi-structured interviews with the experts in the built environment and a preliminary decision-making matrix was generated, aiming to provide guidance to the architectural designers on how to effectively use current rapid prototyping technologies within design processes.

Keywords: Rapid Prototyping, Model Making, Complex Surfaces

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INTRODUCTION

Architects use many forms of representation for their designs, ranging from physical to digital, two-dimensional to three-dimensional, sketches to drawings, from renderings and animations to movie clips. Among all these representational media, the physical model helps designer a great deal in portraying their ideas. Whether it is a student conveying a design idea across to lecturers, an architect presenting their design to a client or an architect giving building instructions to a contractor, physical representation and model making is considered an integral component of the architectural design process.

For many centuries, models have been used to explain complex construction details to builders and considered to be fundamental tools of design (Gibson et al., 2002). According to Millon (1994), Michelangelo, when designing the Vatican used physical models as an intermediary to describe construction techniques and form of internal spaces to both clients and stone masons. Similarly, Palladio in the 16th century used intermediate models of wood as full-scale mock-ups to explain buildings to masons (Burns, 1991; Oxman and Sass, 2005). The craft of architectural model making seems to have been overtaken by recent developments in the area of digital renderings and virtual reality technologies, but the importance and relevance of physical models cannot be undermined. Physical models help the designer not only in exploration of ideas, but also in communicating such ideas, as demonstrated by Michelangelo.

Prior to the advent of digital revolution, architectural models were generally made by hand by skilled craftsmen. This process was time consuming and required highly skilled laborers. Given manual nature of the process, physical models were not optimally used to review various design iterations. In contemporary Computer-Aided-Design (CAD) driven processes, computer modelling is used to generate various iterations of virtual models. Due to the very nature of architecture as a discipline in which the visuals are acting as part of the total sensorial experience, it is still necessary to produce physical models at the key stages of the design.

As suggested by Pham and Gault (1998), prototyping is an essential part of the product development and manufacturing process, required for assessing the form, fit and functionality of a design, prior to investment being made. In early stages of the design process, it is crucial for the designer to understand choice of Rapid Prototyping (RP) technology. Recent advances in rapid prototyping technologies allow for development of solid physical models directly from CAD files, rapidly and precisely. Different rapid prototyping processes have different impacts on the product itself, due to varying delivery of design and communication ideas. Mellis (2011) highlights that some processes are more relevant for intricate designs, and can only be produced by specific prototyping technology such as 3D printing. On the other hand, Kolarevic (2003) states, to accelerate the design process, a faster prototyping process such as subtractive (i.e. CNC-milling) might be another choice of communication and representation. Thus, different prototyping technologies have their own capabilities for delivery of design intent.

This paper starts with an introduction of architectural model making, showing that due to technological advancements there is crucial demand for Rapid prototyping processes in the architectural design process. For architectural designers with little or no knowledge of Rapid prototyping technologies, a brief explanation was given. This is followed by a research experiment that analyses practical use of rapid prototyping technologies, which are being used in architectural design process. It explores how rapid prototyping could allow architects to alter the way they think, during their design process due to tremendous technology improvements to test and manipulate designs, before they are actually manufactured. Right after the experiment semi-structured interviews undertaken in order to formulate guidance decision matrix for architectural designers. This is followed with a discussion on benefits of RP technologies in relation to architectural modelling in academia and practice during the design process. Finally, a conclusion was presented for the potential of actively using RP technologies during the design process.

LITERATURE REVIEW

Rapid prototyping is defined as "the ability to generate models directly from computer-aided design data in a very short time" (Tut et al.,2010). These technologies are based on group of techniques to quickly generate a scale model or assembly parts using 3D input data (Zee, 2014). The use of RP technologies provides an inexpensive, efficient and rapid method for designers, to test and validate the product from the early design stage, up until the finishing stage (Sanchez et al., 2005). As a result, novel prototyping technologies (RP) made it possible for rapidly generate physical models and formed a feedback mechanism for new design alternatives and iterations to explore (Tomohiro et al., 2016).

Design is a process with different development stages to test and evaluate the design. Each design stage requires various scale models to evaluate the design product. Ryder et al., (2002) categorized three types of models according to the stage of the design project: 1. Feasibility Model, 2. Planning Model, 3. Final Project Model. Ryder et al. (2002) further explained that, *the feasibility model* is created to convey the concept of the design, with not much detail is added and sizes are usually small, but with the general form of the design. *The Planning model* is created when more details needed to be conveyed at a higher quality than the feasibility model. Therefore, the designer can portray more clear understanding of the design with its relationship to its context. *The Final Project Model* is showing the actual design once it is completed. In practice, this is the type of model that is shown to the clients and public. In school, this could be the model for the final design intent. Further Kolarevic (2003) highlighted that introduction of digital prototyping enabled architectural designers to produce scale models of their designs according to the level of detail they need to evaluate or communicate. This will be further explained in the design experiments.

RP technologies can be categorised into two broad categories (i.e. *Additive* and *Subtractive* processes). This classification is based primarily on the process of manipulation of material. The *Additive processes (i.e. 3D printing)* produce the prototype through layer by layer addition of material, until the model is complete (Mellis, 2011). This process starts with nothing and then builds up the model to completion, just like the normal construction technique. The *Subtractive processes (i.e. Computer-Numerical Control(CNC)-milling)*, however, are those in which the material is produced by the gradual bit by bit removal of material from existing block of material (Kolarevic, 2003). This is the direct opposite of the additive process, as it starts with a large material, which is formed into the desired product through an intricate process of subtraction.

In recent literature, rapid prototyping technologies have also been broadly classified based on an initial form of the material used by machines in the production of its prototypes. Based on material form, rapid prototyping systems can be categorised into (i) Liquid-based (ii) Solid-based and (iii) Powder-based. A comparison of rapid prototyping technologies is presented in Figure 1, based on Kruth's (1991) work. Figure 1 has been adapted in order to show the various different rapid prototyping technologies. Among the various technologies presented in Fig. 1, this paper reviews two of the most commonly used technologies (i.e. Three-dimensional Printing (Additive) and CNC Milling machine (Subtractive)).The selection was made due to their greater ability to fabricate complex surfaces in comparison to the other technologies and as they form desktop-size (non-industrial machines) devices to fit in the office or schools .The machines are simple enough to be operated by students or architectural designers with some prior training with no serious technical skills (De Brujin, 2010).

<<Insert Figure 1 here>>

Figure 1: Classification of Rapid Prototyping based on initial form of material, Kruth, (1991) in Pham & Gault (1998)

Key: Solid Ground Curing (SGC), Fused Deposition Modelling (FDM), Selective Laser Sintering (SLS), Three-Dimensional Printing (3DP), Laminated Object Manufacturing (LOM), Electrosetting (ES), Balistic Particle Manufacture (BPM), Three-Dimensional Welding (3DW), Gas-Phase Deposition (GPD), Spatial Forming (SF), Stereolithography Apparatus (SLA), Liquid Thermal Polymerisation (LTP), Beam Interference Solidification (BIS)

RESEARCH EXPERIMENT

This Section presents the findings of a research experiment carried out in order to establish the effects of the use of rapid prototyping technologies on the architectural design. The experiment explains how the use of these technologies could impact or aid the overall design outcome. For the experiment, ROLAND Modela Pro II MDX-540 CNC-milling machine (Fig.2a) was used, alongside ZPrinter 450 3D printer (Fig. 2b). Each Rapid Prototyping machine use different working principles and software for operation. These machines were used in testing the accuracy of the design geometry in terms of protecting the design intent within the production process of each model.

<<Insert Figure 2 here>>

Figure 2: (a) CNC-milling machine & (b) 3D printer

This research compares rapid prototyping with traditional physical modelling techniques and the research experiment highlights this potential by using it in the development of a design. The research highlights the benefits of the integration of rapid prototyping into the digital architectural design process. The following section discusses the project briefly and explains the aspects of the design, which were pivotal to the choice for design experiment.

The design used in the experiment involved researchers' small scale pod design (geodesic dome geometry), that was created using Rhino 3D software (Fig. 3). The small-scale pod design was selected for the experiment, to limit scope of the work. The design was considered suitable for the experiment for its geometry, which consisted of triangulation of facets on its dome and consisted of an opening in the front. The design experiment carried out to test the constructability of the pod and its geometric features using two RP technologies and as such to establish the link between the uses of these technologies and design process.

<<Insert Figure 3 here>>

Figure 3: Virtual views of the pod design

Two prototypes were produced with the aid of two different RP machines, CNC milling machine and 3D printer. The following sections present the process of making two prototypes. The modes of operation and requirements of using these machines were discussed in detail.

Prototype 1 using CNC Milling

The first prototype was made using CNC milling machine. ROLAND Modella ProII MDX-540 milling machine was used in producing this particular model. The only two requirements for the production of this prototype was a 3D model in .stl file format and material for milling. To initiate the milling process, the origin of the material should be set and the milling tools should be replaced (Fig.4a,4b,4c & Fig.5a,5b,5c).

<<Insert Figure 4 here>>

Figure 4: (a) Handy panel showing coordinates, (b) Setting the origin on the working piece with Handy Panel (c) CNC milling machine before milling operation

<<Insert Figure 5 here>>

Figure 5: (a) CNC milling machine tool installation door, (b) Tool installation per its diameter (b) Final clinching diameter tool with screwing tool

The machine uses a software called MayKa Expert, version 7.0. The first step was to import. stl format 3D model to operating software. The scale of the model could either be predetermined or chosen based on the size of material to be used in milling. If the object to be cut is more detailed, various types of cutting phases can be applied such as rough cutting and finishing together with their parent milling tools. The finishing process depends on the complexity of the geometry and surfaces. Once the settings were done with the computer software, the actual fabrication started its rough cutting process (Fig.6 & 7).

<<Insert Figure 6 here>>

Figure 6: (a) import .stl 3D model into MayKa, (b) define material block size within software environment (c) & (d) Simulation of the milling method (Rough Cutting and Finishing)

The software simulates the pattern for milling which is sent to the machines, in the same way printing jobs are sent to the printers (Fig.6c & 6d).

<<Insert Figure 7 here>>

Figure 7: Software showing parameters of sweeping (a) Tool depth, (b) Milling tool information, (c) Sweeping simulation

In addition, it is possible to control the motion, feed rate, operation of the spindle drive tool changes and other operational parameters by the help of handy panel to accelerate the milling-process. The major aim of the utilization of CNC milling machine was to observe the design intent, in terms of representation, accuracy and effectiveness of the total geometry and its surfaces. Figure 8a & 8b shows the 3D milling process in action.

<<Insert Figure 8 here>>

Figure 8: Views of CNC milling process (a) CNC milling machine in operation, (b) CNC milling machine operating rough milling process

PRODUCT 1

The model was produced at a scale of 1/100 due to plate size and tool length of the machine used, which was suitable to evaluate the facets and the other sections of the geometry. The final product was a closed geometry although the original file sent to the machine was open (Fig. 3 & Fig.9). In addition, on the base point of the final product, some tiny protrusions were visible (Fig.9c), by which it can be inferred as a constraint of the milling tool length used for this implementation. The milling tool could not reach the 1-2mm to the bottom of the model. The fabrication process of the total model took approximately 1 to 2 hours with its cleaning process.

<<Insert Figure 9 here>>

Figure 9: CNC milled model views

Prototype 2 using 3D Printing

The second prototype was built using Z Corps's 3D printer. To print a 3D model a few considerations had to be made such as, the thickness of the model to be printed (because a thin model would directly mean a fragile model) and the required scale (considering the maximum printable size of 203x254x203mm). Also, three-dimensional printing required a completely closed and composite model. This is because it prints the objects in layers and spaces would only result in a fragile and broken model. The software for the printing was developed by Z Corporation (Fig.10) has the facility to view each layer of the printing to be done and hence gives the possibility to evaluate any problem areas. The visible yellow line shows the produced mass in section view and the plan view of the printed parts were also shown by the operating software.

<<Insert Figure 10 here>>

Figure 10: Images showing additive fabrication process layer by layer fashion (a&b&c)
(d) Picture showing elapsed time of the 3D printing process

After the allotted time for 3D printing finalised, the model was collected from the machine's envelope, which was full of unused powder (Fig.11). The 3D printer fabricates layer by layer therefore according to its working fashion. The powder that was not used, was visible over the created model, which was cleaned by a vacuum and a soft brush after. Because of the model's fragile walls ,it was very carefully carried out of the envelope and after that it had to be glued in order to strengthen the final 3D printed model. The powder used which is high in cost can be reused after the collection with the vacuum tool back into the machine's container.

<<Insert Figure 11 here>>

Figure 11: Image showing powder removing processes after 3D printing

PRODUCT 2

The final product was at a scale of 1/50 of the design geometry which is very fragile because of its thin walls (Fig.12). However, an exact replica of the design intent produced. The 3D printed model fabricated in approximately 6 hours, after fabrication the model left 45 minutes for drying, right after that the powder around the artefact vacuumed, and glue applied onto the surface. In total, prototyping process took 6-8 hours.

<<Insert Figure 12 here>>

Figure 12: Views of Glue applied final 3D printed model

Comparative Analysis & Results

The analysis of the findings of the experimentation on each product was done according to their accuracy of delivering design intent / representation.

CNC milled Model: The experiment carried out on the CNC cut model showed that there were some limitations in representation of the design. Some details were lost because of the length of the milling tool and the axis constraints. The opening in front the pod, and the dome's inner space were lost. Although the. stl format model that was sent to computer software was accurate in showing the open space, the machine recognized the design as one solid mass. Another constraint detected was the scale of the plate. The scale of the product could not exceed the plate size. The tool length was not enough to reach very bottom of the geometry, therefore, in the final product there were some visible tiny protrusions around the total mass. The delivery of the facets on the dome, were visible enough to communicate the design intent.

3D printed Model: The 3D printed product was the exact replica of the actual 3D pod design produced by the design software (Fig.12 & Fig.3). The final product was very realistic and accurate as per idea delivery and the design intent was protected. The representation was realistic and relevant. The 3D printed design outcome proved that design intent was maintained. However, the product itself was very delicate to carry.

The results of the experiment showed that 3D printing is accurate in complex geometries and surfaces in terms of its delivery of design intent. It can fabricate the exact replication of the 3D design that was created by software. On the other hand, CNC milling experiment showed that it is obvious that the geometry was accurate on the surfaces of the geometry, however, it was inaccurate for the empty space representations.

The experimentation results were evaluated by five semi-structured interviews conducted with the architectural practitioners and design academics in the field of architecture. Final products were shown to the experts in comparison (Fig.13) The interview results suggested that accuracy level of the 3D printing machine was very highly dependent on the material types that additive technology uses. Because based on the 3D printer's powder type, the product can be very fragile and could be very difficult construct layer by layer principle. Other points argued for 3D printing was that slow processing time by its layer by layer fashion and, high cost of materials. In this case, quick model generation from CNC milling machine made it more preferable to use in comparison to the 3D printer. However, 3D printer showed that it was very user friendly in comparison to CNC milling machine. Therefore, CNC technologies could be an option to deliver ideas quickly on different stages of the design for their low cost and speed. CNC milling machine was very accurate on surfaces and could rapidly produce mass models at an optimum level. However, precise models with more accurate surfaces could be fabricated with 3D printer. Typically, models created with 3D printer are brittle, but can be strengthened by different powders and adhesives. The biggest disadvantage of 3D printer is the post-processing which can be messy and tedious, because of the powder that remains after the 3D printing needs to be cleaned and vacuumed from the fabricated model. Both machines require no monitoring during the process once they are set for the fabrication. In conclusion, although the rapid prototyping technologies are very convenient to produce various models due to different design phases, the machines require some level of training for operation.

<<Insert Figure 13 here>>

Figure 13: Views of design products used during semi-structured interviews;subtractive (b&c) and additive processes (a&d)

According to the evaluation of the experiment, in order to provide guidance to architectural designers, the researchers generated a preliminary decision-making tool (Table 1) and verified the results with the experts during the interviews undertaken. Table 1 forms an evaluated matrix for designers to consider prior using the rapid prototyping technologies, as their accuracy, delivery of design geometry, process speed, cost of material, and user friendliness per rapid prototyping technology and their operating fashions.

<<Insert Table 1 here>>

Table 1: Decision making matrix for rapid prototyping
Key: Adequacy: ++++, Inadequacy: +

The outcome of the design experiments can be supported by Seely's (2004) extensive research on rapid prototyping technologies. Although the modes of operations and functions differ to a very large extent, however some general grounds can be compared as user-friendliness, size, materials, interaction, speed and price.

DISCUSSION

This study reviewed benefits and demerits of the rapid prototyping technologies carried out by the application of two experiments. Moreover, the benefits and supportive role of these technologies in the architectural design process analysed and practical results were given by forming a decision-making matrix.

The practice and the educational requirements for the prototyping are different. For students, the aim is to learn; therefore, they have the freedom of testing various prototyping processes in different design stages, on the other hand the architectural designers in the practice, the aim is to quickly and accurately deliver the design ideas to the clients. New generation of architectural practitioners are partially aware of the rapid prototyping technologies. However, many of them are not aware of the benefits of current digital prototyping technologies, minor number of firms are using these technologies in various design stages. Benefits of the rapid prototyping technologies should be represented to the architectural field in order to maximize design performance during design stages. In conclusion, the advantages of the RP technologies are required to be introduced both to academia and to the field of architecture and construction, as the integrated essential part of the design process.

CONCLUSION

Technologically driven change has always been a catalyst for new ideas in architecture, and today, digital technology is a key agent for innovation in design and construction (Klinger et al 2001). Timely assessment of design concepts has given the possibility of generation and elaboration of new ideas. A digitally prototyped model is something greater than an image on the computer screen, it gives the possibility to test accuracy of the digitally driven designs. RP offers architectural designers the ability to think of ways of rationalizing computed design into tangible medium allowing a variety of constructible designs rather than abstract objects. With the help of RP the acceleration of process achieved accurately. The data is protected during the stages of design process which has been a challenge during many years in the design practice. A rapid prototyping of a model means that more designs can be considered and tested in a shorter period of time. Potential manufacturing problems that are caused by the part of design can be identified before full fabrication begins. Not only does the design process move quicker, but the quality of the design is likely to improve as well.

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Tables and Figure Caption List

Table 1: Decision making matrix for rapid prototyping
Key: Adequacy: ++++, Inadequacy: +

Criteria	CNC milling (Subtractive)	3D printing (Additive)
Accuracy	+++	++++
Surface Details	++	++++
Process Speed	++++	+
Cost of materials	++++	+
User Friendliness	++	++++

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Figure 1

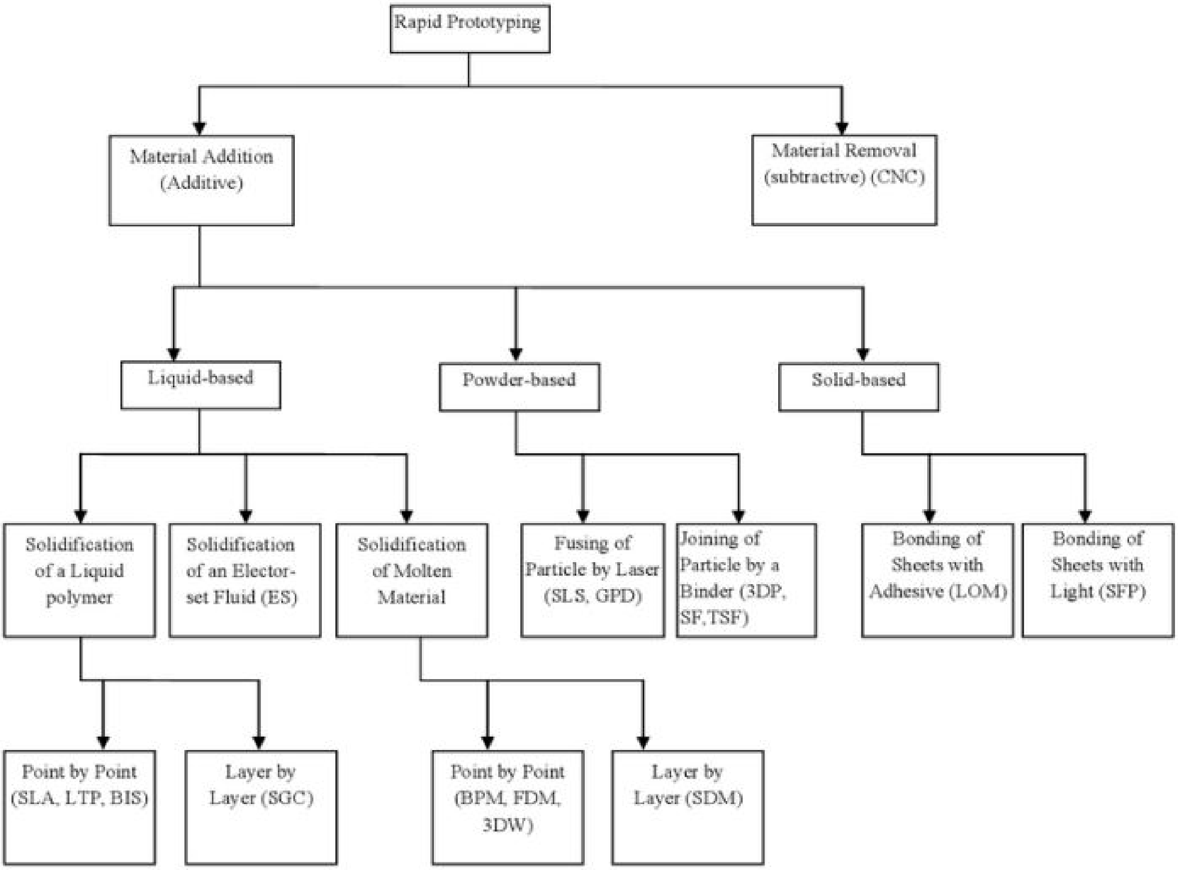
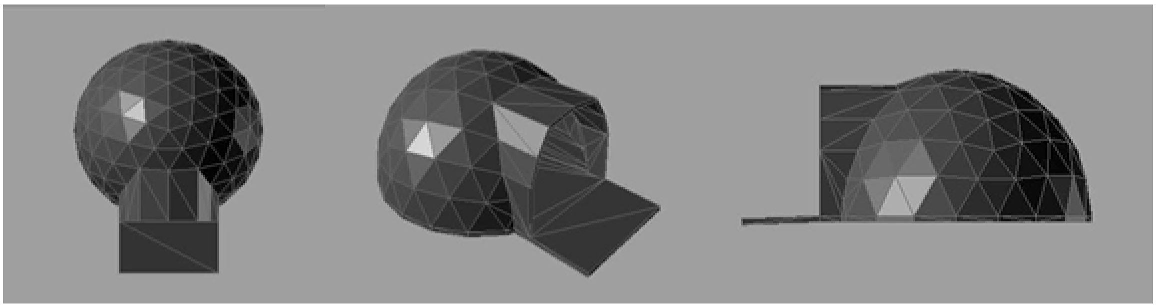


Figure 2

(a) (b)

Figure 3



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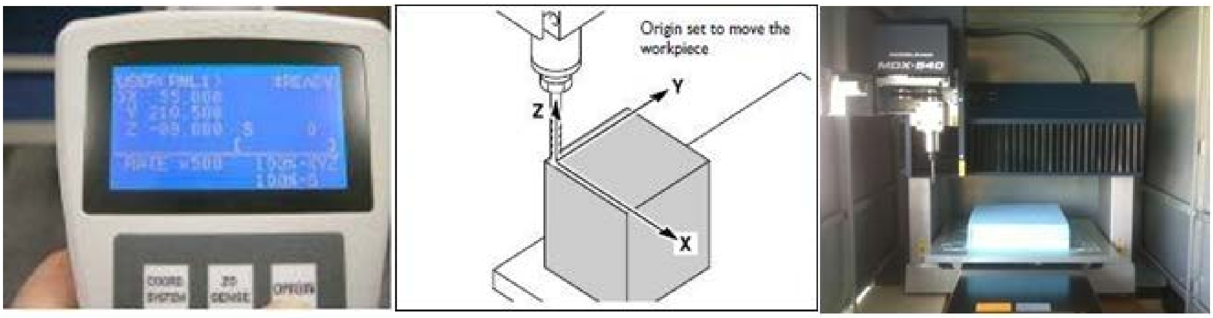


(a) (b) (c)

Figure 5

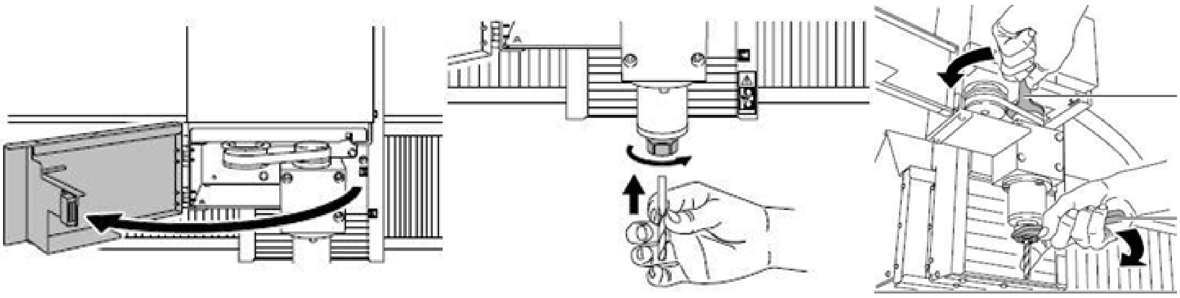
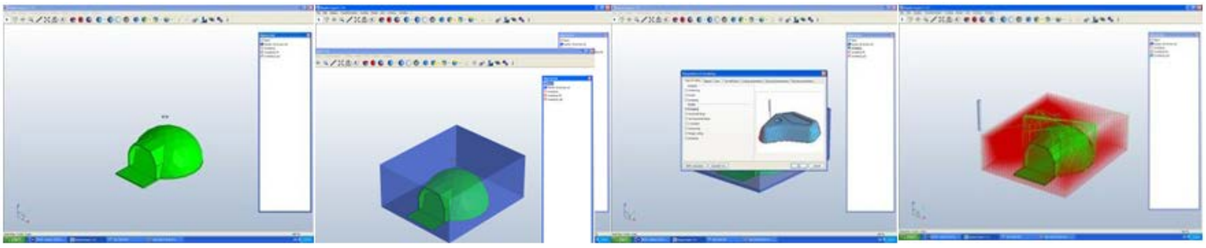
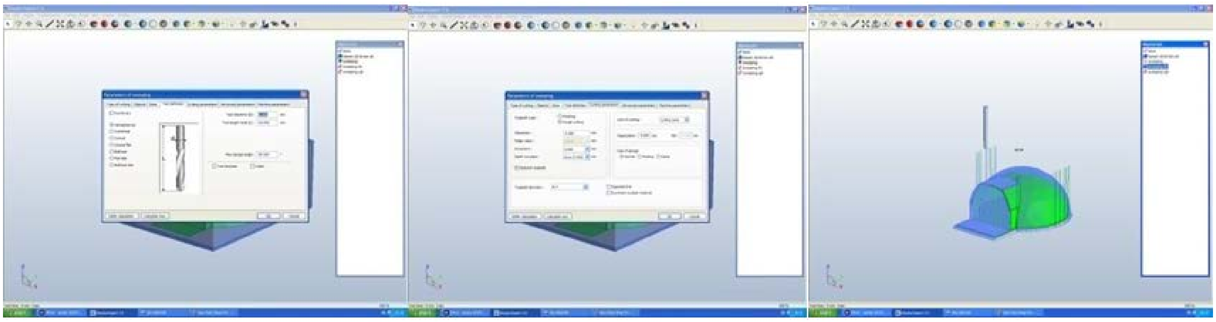


Figure 6



(a) (b) (c) (d)

Figure 7



(a) (b) (c)

Figure 8

(a) (b)

Figure 9

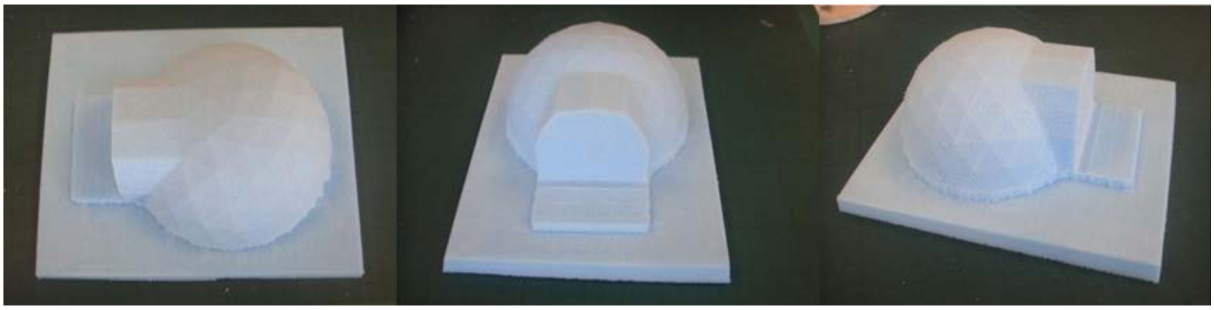
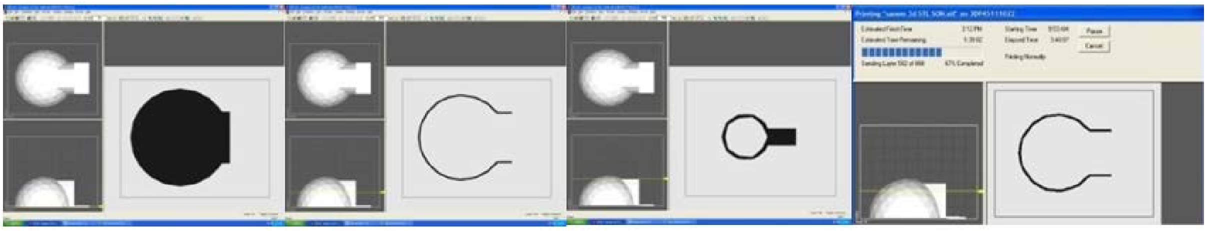


Figure 10



(a) (b) (c) (d)

Figure 11

Figure 12

Figure 13

(a) (b) (c) (d)