INTRODUCTION

Building architectural models is an integral part of the design studio. In architecture programs physical model building begins right in the freshman year and carries through into the design studios. Physical models can be created at each point of the design process from the conceptual phase through to the final design. The primary focus of a physical model is visualization. Models help us understand form, spatial organization, scale and proportion. Building physical models requires students to comprehend the design in its totality as they have to resolve all aspects of the design in order to be able to build the model (Day). Consequently a well-built model enables the audience to then get a complete view of the design. Through an internal grant received at Western Kentucky University, (WKU) an investigative study was conducted to examine the feasibility of using the rapid prototyping (RP) process for building models in the architectural design studio.

The goals of the study were primarily to compare the traditional architectural model building process and three-dimensional (3D) printing with regards to (1) process flow, (2) time, (3) material (variety and ease of handling) and (4) precision. Three designs were selected and physical models were made using the traditional model building methods as well as the RP process. The paper highlights the path used to arrive at the three final models and compares and contrasts the approaches. The unique setup of the Department of Architectural and Manufacturing
Sciences (AMS) proved to be a great facilitator for this project. The traditional model building process was carried out in the designs studios and RP was carried out in WKU's Mitch McConnell Advanced Manufacturing and Robotics Laboratory.

Traditional Model Building within Architecture

Physical model-making is the process of creating physical replicas of designs (Orr, 2008), at a reduced scale compared to the actual size of the object. Building models has always been a very important part of the curriculum in architecture schools. Models are used by students to understand form and space, figure out complex designs, convey design solutions and as a presentation tool. Physical models are used as visualization tools that overcome the limitations of two-dimensional (2D) images (Tucci, Bonora 2011). Students are taught the basics of model-making right in their freshman year where they create sketch models with materials such as cardboard boxes, paper and other scrap materials. The students also experiment with finer model making materials such as paperboard varieties, wood and acrylic. They are taught techniques of material selection, cutting, gluing and presentation. The skills acquired are carried forward to the design studios. In the design studio, the model building process begins with design sketches; once a design has been finalized and drawings prepared (either hand drawn or computer aided) the scale of the model is decided, materials selected to create the model and the building process begins. The building process has three main steps, (1) drafting the model outline onto the material selected to build the model, (2) cutting out the pieces, and (3) gluing the pieces together to create the desired shape. Though model building is a very effective tool in communicating design ideas there are numerous drawbacks to building a model which include but are not limited to poor quality, human error (Agarwala et al., 2009), time constraints and disinterest on the part of the student.

Rapid Prototyping

Rapid prototyping (RP) is a manufacturing process through which the user creates a physical model directly from a computer-aided design (CAD) (Liou, 2008). It starts with the creation of the 3D CAD model which when
complete is converted to Stereo lithograph (STL) format. The STL format is used by the 3D printer to produce the physical model. Of significance is the fact that from this point on involvement by the model builder is minimal. The model build can take anywhere from a couple of hours to an entire day. On completion the model is immersed into a wash tray where ultrasonic washing dissolves the support material providing for a clean prototype. Since the model is built layer-by-layer without extraneous tools complex geometrical shapes can be modeled (Liou, 2008). There are liquid-based, solid-based and powder-based RP processes for creation of the physical model. The solid-based process which is also termed as the extrusion-based process feeds material in solid wire form and then melts it into the desired shape and the model is created (Liou, 2008). During this investigation the solid-based process with Fused Deposition Modeling was used to create models for the study.

**STUDY PROCESS**

WKU awards Faculty-Undergraduate Student Engagement (FUSE) grants to encourage undergraduate student research. The student works on a selected research topic under the guidance of their faculty mentor during the funding period. The study discussed in this paper was conducted as part of a FUSE grant received during spring 2012 and was undertaken during the fall 2012 semester. Three models typically built by students through the course of their study were used for this investigation. For the traditional modeling approach Chipboard was used as the material for building the models. Models 1 & 2 were re-built using the traditional as well as RP process. For model 3, an existing hand built model was used for this study while it was re-built using the RP process. The 3D printer used for the RP process was the Dimension Stratasys, using ABS plastic as prototyping material. The 3D printer available in the laboratory could build models to the maximum size of 8"x8"x8", and these dimensions were a factor in selecting the models being used for this study.
The first model (figure 1), involved the amalgamation of three shapes, a triangular volume, a rectangular volume and a curved surface volume; a model typically built by Architectural Science (AS) majors in their freshman year.

Figure 1: Model 1

The second model (figure 2), involved integrating three planes into a cube to establish hierarchy, rhythm and create balance; a model built by AS students in their junior year in the design studio. The third model (figure 3),
involved the building of a single story residence, undertaken by the students in their freshman year. Models 1 and 2 required students to create design concepts before beginning the building process, on the other hand at the start of model 3 the students were provided with a set of drawings to build the model. Table 1 lists the models built, the number of iterations, the time taken to build each model and the cost of materials used to build the model.

Figure 3: Model 3

DISCUSSION

During observations of the traditional and rapid prototyping processes, the advantages and disadvantages in making models using these processes was noted and recorded. Figure 4 illustrates the process flow for both the traditional model building and rapid prototyping processes. Both the processes begin with the design sketches of the model to be built. With the traditional model building process the builder has the option to select materials that would be appropriate for and convey the intent of the design, while with 3D printing the material is restricted to the type of printer being used. The traditional model building process requires the builder to be involved through all the steps of the process, while in RP the involvement is up to the generation of STL files after which there is no involvement till the build is completed by the printer.
Table 1: Comparison of Traditional Modeling and RP

<table>
<thead>
<tr>
<th>Model</th>
<th>Design Sketches (hours)</th>
<th>Traditional Model Building Process</th>
<th>Rapid Prototyping Process</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Drafting (hours)</td>
<td>Building (hours)</td>
<td>Cost ($)</td>
</tr>
<tr>
<td>I</td>
<td>1.5</td>
<td>5.5</td>
<td>$ 10</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>17.0</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>0</td>
<td>5.5</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>0</td>
<td>4.5</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4: Process Flow of Traditional Modeling and RP
To further analyze, compare and contrast the two approaches we look at table 1 above. The design sketches are common between the two approaches. Design sketches were provided for model 3 hence there is no time designated in the corresponding cell in table 1. In an academic setting, when students build a model using the traditional method it is usually a single attempt, since it is labor intensive. In contrast for a student attempting a RP model for the first time there may be several iterations of the same model as seen in table 1. The student built four iterations of model 1 using the RP process. In the first attempt (figure 5), the near infinitesimal area of the triangular tip resulted in a failure of the material to bond between the rectangular volume and the triangular volume.

![Figure 5: Model 1, First Attempt](image)

The second iteration contained flaws in scaling and the resulting model was approximately twice the desired model scale, as seen in table 1 the corresponding time required for the iteration was 17 hours. The problems encountered in the first two iterations were resolved in the third attempt. All the three iterations had surface imperfections. While the printing process for model 1 was ongoing the student started working on model 2. Three iterations of model 2 were built. In the first attempt the student made an error on the thickness of the edges making them 3/8” instead of 3/16” (figure 6). This was rectified in the second attempt but these two models also had surface imperfections. On investigation, it was found that the ABS plastic cartridge needed to be replaced. The cartridge was replaced and the fourth iteration of model 1 and third iteration of model 2 were re-printed achieving the desired result (figure 7).
The third model was printed twice. In the first attempt the walls of the house were too thin when printed and the floor did not print (figure 8). The student realized that the walls and floor were not drawn to the required minimum thickness when creating the 3D model in CAD. Horizontal planes are a particularly important detail to be checked for 3D printing since a minimum number of layers of material are need to be carried out over a relatively
large surface area (compared to the non-horizontal elements) for the floor to be printed properly. This was then corrected and successfully reprinted by the student (figure 9).

Figure 8: Model 3, First Iteration

For the traditional approach models 1 & 2 were re-built by the student. Figure 10 illustrates the quality and precision of model 1; considerable time was spent by the student to build the model to achieve the desired results.
Some of the visible edges of the model need to be better aligned, but on the whole the model is well executed. The traditional approach to model building allows students to build quick study iterations before attempting a serious build. While working on model 2 the student spent time on the design process and built three study models of paper (figure 11). The results of the final model can be seen in figure 11; the student did not spend adequate time on this model and as a result the edges are not well aligned due to imperfections while cutting and glue is evident on the surfaces.

Figure 10: Model 1, Using Traditional Model Building Process

Figure 11: Model 2, Study Model (left) & Final Model (right) Built Using Traditional Model Building Methods
Figure 12 illustrates the results of model 3; this model was built during a prior semester in a freshman class. The student put in considerable time and effort in the building process and this is evident in the level of detail. The model was built over three weeks with, in class time being 4 hours per week and 5 hours of time outside class in the three week period to build the model. The student had the freedom to select materials which would allow the model to have the desired finish.

![Figure 12: Model 3, Built Using the Traditional Model Building Process](image)

**RESULTS**

The first two models presented deal with fundamental form and shape; on comparing the models built using the two approaches RP models are more precise and have better defined edges. Using the RP process in model 1 enabled the student to integrate the model with a higher level of accuracy since it involved extrusion of material from one volume to allow the other volume to integrate. In traditional model building, extrusion is considerably tricky, difficult and is dependent on the skill of the model builder. In model 2, which should have been an easy model to build manually because of its defining geometry, the disadvantages of traditional model building are apparent. Edges are not perfectly aligned, glue is visible and the edges are not straight. Model 3 clearly shows the
strengths of the traditional approach. In the hand built model there are at least three materials used to fabricate the model. The model is well defined in terms of preciseness. Most importantly this model is completely finished and ready to present to a client or reviewer. The RP model on the other hand is a base model which requires additional work (either automated or manual) to bring it to the same level of finish as the hand built model. Model 3 indicates a potential pathway to integrate RP with the approach of traditional model making in the design studio. Students could work on a relatively complex design and create a 3D drawing to enable the production of a base RP model, which would then be augmented by traditional model making methods to produce a finish that would meet or exceed expectations. The advantages of the RP base would be precision and well defined edges and surfaces, while the benefits of using the traditional approach would be a greater selection of material and addition of detailed features that would not be easily achieved by RP.

The time spent in building the RP models comprise two components, (1) the time spent in producing the 3D CAD model and (2) the time taken by the RP system to print and wash the model. As seen in table 1, for the traditional hand built models a cumulative of 4 hours for drafting and 22.5 hours build time was used by the modeler for a total of 26.5 hours. For the RP approach a cumulative of 7.75 hours was used for drafting while build and wash time was 152.5 hours for a total of 160.25 hours. These figures account for all iterations for both approaches built. Since the build time in RP requires minimal involvement by the student builder, the time spent by the student would be the time spent on 3D CAD. Table 2 (shown below) which is a derived subset of the numbers from table 1 gives a comparative idea of student involvement in the two approaches.
Table 2: Subset of Table 1 Showing Time Comparisons

<table>
<thead>
<tr>
<th>Model</th>
<th>Traditional Model Building Process</th>
<th>Rapid Prototyping Process</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Drafting + Building (hours)</td>
<td>Drafting (hours)</td>
</tr>
<tr>
<td>1</td>
<td>7</td>
<td>3.75</td>
</tr>
<tr>
<td>2</td>
<td>2.5</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>17</td>
<td>2</td>
</tr>
</tbody>
</table>

CONCLUSION

Traditional model building methods are followed by most schools of architecture. They provide for good study models for students to further their designs. As observed earlier a highly detailed model requiring a wider selection of materials would benefit from the traditional model building approach. This is significant when building architectural design models showing lots of features such as building finishes and landscaping.

This study finds that while RP has the advantages of better precision and edge definition, there are factors that need to be considered for RP to be efficiently carried out.

1) Training students in 3D CAD: This is a necessary prerequisite for RP usage. Currently students are formally trained in 2D CAD and course changes will need to incorporate 3D CAD if model making using RP is to become a part of the AS curriculum. This would also include instruction in scaling so that the iterations of the same model that were carried out can be avoided.

2) Technology: The RP system used in this study was good for all three models but was an optimal choice for the first two models. Additional investigation is required to see how the third model could be built using RP to approach the finish achieved by hand built models.

3) Cost: Critically, cost is an aspect where the traditional approach is clearly a more economical approach. The cost comparison and cost variance per iteration for RP to traditional model building was found to be 3.1:1 to
10:1. Assuming that training and preparation would reduce iterations to one per model the cost is still at least 3:1 for RP to traditional model building.

While traditional model building is a skill that is required of every architecture student, RP is an additional approach to model building that students of architecture would be well advised to add to their model building skills. As students graduate and join architectural practices, their experience with 3D printing could raise awareness and encourage practitioners to adopt the RP process for model building (Kirton & Lavoie 2005).

ACKNOWLEDGEMENTS

The authors would like to thank WKU’s Office of Academic Affairs and the Office of Research for the grant which made it possible to carry out this investigative study. We would also like to acknowledge the faculty in charge of the Mitch McConnell Advanced Manufacturing and Robotics Laboratory for their advice and assistance in the 3D printing process.

REFERENCES


