AN ANALYSIS OF THE APPLICATIONS OF RAPID PROTOTYPING IN ARCHITECTURE

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Abstract. Rapid prototyping (RP) techniques are widely used within the design/manufacturing industry and are well established in manufacturing industry. These digital techniques offer quick and accurate prototypes with relatively low cost when we require exact likeness to a particular scale and detail. 3D modeling of buildings on CAD-systems in the AEC sector is now becoming more popular and becoming widely used practice as the higher efficiency of working with computers is being recognized. However the building of scaled physical representations is still performed manually, which generally requires a high amount of time. Complex post-modernist building forms are more faithfully and easily represented in a solid visualization form, than they could be using traditional model making methods. Using RP within the engineering community has given the users the possibility to communicate and visualize designs with greater ease with the clients and capture any error within the CAD design at an early stage of the project or product lifecycle. In this paper, the application of RP in architecture is reviewed and the possibilities of modeling architectural models are explored. A methodology of developing rapid prototypes with 3D CAD models using methods of solid freeform manufacturing in particular Fused Deposition Modeling (FDM) is presented and compared against traditional model making methods. An economical analysis is presented and discussed using a case study and the potential of applying RP techniques to architectural models is discussed.

1. Introduction

Conventional model making or prototyping in the traditional sense is a long-standing and well established practice within the AEC sector. Architects use models as visual aids in presenting new designs and the primary reason of having a physical prototype model was to visualize the concept of a design. Thus, a prototype is usually required before the start of the construction phase. However, creating architectural models can be an expensive and time-consuming task. The fabrication of prototypes has been carried out in many ways, historically using conventional manual methods such as carving, castings, moulds, joining with adhesives etc, and utilizing basic materials types aluminum, zinc, urethanes, wood, etc. Most model makers would carve a model by hand, but this involves using highly skilled craftsmen. With the aid of rapid prototyping (RP) technology, labor is said to be de-skilled, our views differs as skilled labor is required to operate the CAD equipment, but there is no doubt there is a great potential for models to be created with greater speed and accuracy.

While rapid prototyping technology has been used for years in industrial design, many companies like "LGM" are currently leading the industry in applying this tool to architectural and development applications. Models help contractors, engineers, and architects in several different ways. A well-built model is a functional and informative tool intended to solve potential problems. The application of RP technologies and digital manufacturing offer notable potential to AEC technologists and RP researchers with the focus on 3D modeling of buildings within the application of architectural model making in the AEC sector. Revisions in development and design can be derived from an accurately detailed model. Chua et al 2003 describe that development of CAD and advancements in manufacturing systems and materials have been crucial in the development of RP. Wieneke-Toutaoui and Gerber (2003) have reported this technology is fast developing and is more than competitive to traditional model building techniques considering time and degree of detail. RP in model making within the AEC sector, showing the difference made; now days it becomes possible to involve designer, sells department and the company's clients in design processes before manufacturing to avoid doing any mistake. The objective of the study presented in this paper was to compare between traditional ways of modeling that depends on the craft men to produce architecture models and RP techniques in architecture. To do this comparison, we have modeled ground floor of a building in 3D CAD and a comparison will be made between producing the same model by using Fusion Deposition Modeling (FDM) as the RP method and traditional way of modeling. Software mainly I-DEAS, INSIGHT and DELCAM POWER MILL software were used to calculate time and cost of RP.

In RP mainly two types of processes are used. They are subtractive process and additive process. In this report the discussion will be about exploring these two methods of making architecture models. It is very important to create 3D CAD design before sending the job to FDM machine, there will be procedure to create a 3D CAD design with the aid of one from the available CAD packages. It is possible to simulate the process inside the Insight software to calculate time and the material cost which the machine needs to build the model. In this paper also there is a discussion about the possibility of producing the architecture models by using CNC machine. This is achieved by simulating the processes in Delcam Power Mill software to see whether the machine has the ability to produce the shape with its small details or not. The final part of the paper discusses the cost evaluation by utilizing both methods of modeling.

2. Methodology of 3D Physical Models

2.1. DESIGN 3D MODEL IN TRADITIONAL METHODS.

The traditional method is based upon 2D process that can be generated by architect using software like AUTOCAD, or simple hand sketches. Each single part is made separate by all parts are assembled by using standard model making materials, i.e. glue, balsa wood etc, this process requires skill and is labour intensive, which increases the cost, in addition to this it causes loss of material too.

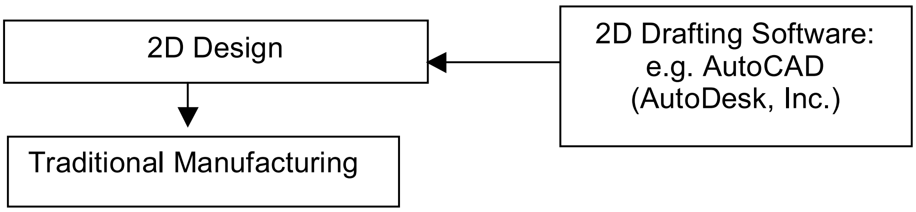

Figure 1: Traditional method of building an architectural physical model.

2.2. RAPID PROTOTYPING

Rapid Prototyping (RP) is also often called Solid Free Form Fabrication (SFF), which refers to a specific class of new manufacturing processes that form parts on a layer by layer basis with minimal user assistance unlike conventional CNC model making, which is performed in a subtractive

manner, removing material from a raw block of material to achieve the final shape of the model.
The common methodology they adopt can be described as follows:

- **3D CAD generation:** A 3D model of the component is generated on a Computer-Aided Design/ Computer-Aided Manufacturing (CAD/CAM) system.
- **CAD Export File:** The 3D computer generated model is then converted into a Stereo Lithography file "STL" format, which is commonly known as a “Triangle File”, as the model is tessellated into triangles. Obviously, as we cannot exactly duplicate the curved form or rounded surfaces with triangles, the accuracy of the model depends on the size of the triangles.
- **Pre-Processing:** A computer program analyses the STL file that defines the model to be fabricated and at this stage the model can be scaled and oriented to achieve optimum results i.e. nesting for maximum machine utilization. The computer program then simplifies the model into 2D cross sections known as "slices", at different Z intervals. After the model has been sliced, it is necessary to create the supports (to support over hangs) that will allow the part to be built in the RP machine.
- **Model Construction:** A fully processed and verified .STL file is then sent to the Rapid Prototyping Machine to be built. Additive material formation method incrementally deposits, cure, or bind very thin layers of material within the "build chamber" of a particular machine. Most build chambers are relatively small, but larger components are routinely subdivided and built in sections.
- **Post finishing:** This step is used to clean and finish the physical RP model. Depending upon the RP method support material can be removed by either an ultra-sonic or can be removed with various hand tools.

2.2.1. RP Experimentation Using Additive Methodology FDM Machine

An RP system enables us to develop a model or prototype within minutes or hours, directly from the CAD design. Design includes all activities involved from the original concept to the finished product. The challenge is selecting the right process for the task. Choosing between the various RP technologies can be difficult, we should ask following questions to make a proper selection.

1. What we are looking for?
2. How long will it take?
3. How much will it cost?

Also, we should be aware about the strengths and weaknesses that are inherent in all RP processes. In this paper we have focused mainly on FDM process.

In the FDM process, a 3D CAD model is sliced into thin layers usually 0.25mm in Z-axis. The tool paths of these sliced layers are used to drive an extrusion head of FDM machine. The basic build size is 203 x 203 x 305mm, large parts can be easily made in sections and joined together. Minimum wall section or feature is recommended not to be smaller than 0.8mm. The building material, in the form of a thin solid filament, is fed from a spool to a movable head controlled by servomotors. Second filament is fed from adjacent nozzle for support material, used to give support for over hanged or cantilever features. Figure 2 represents the steps of the RP methodology adopted in this study.

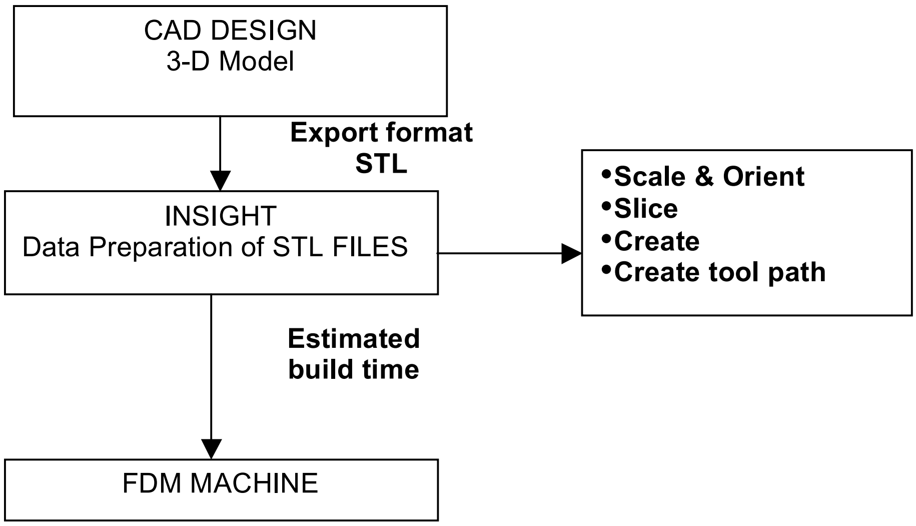

Figure 2: Process flow of RP methodology

2.2.2 3D Design within 3D CAD Software Program

Firstly, a design of a building was constructed based around a typical building in Middle Eastern continent. A 3 D-CAD model was constructed for the ground floor of building, using a series of basic parametric modelling functions such as extrude, revolve, cut, join.

The building was modelled to Scale 1:100 factor, and scaled-down further suit the RP machine. Once the CAD model is constructed by use I-DEAS-10 software program, it was then converted to STL "triangle" format for export.

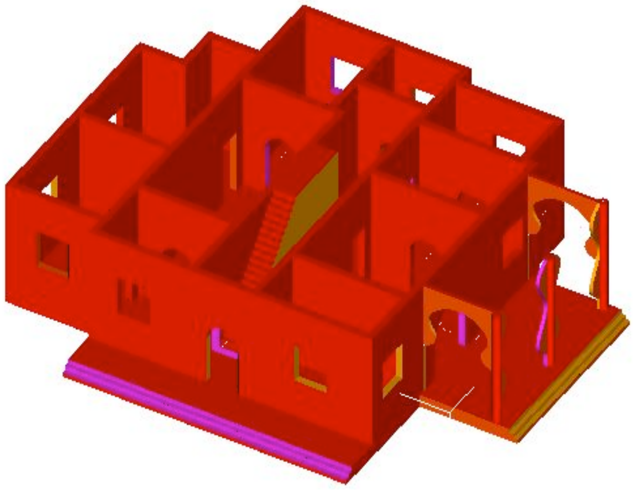

Figure 3: 3D CAD model in IDEAS software

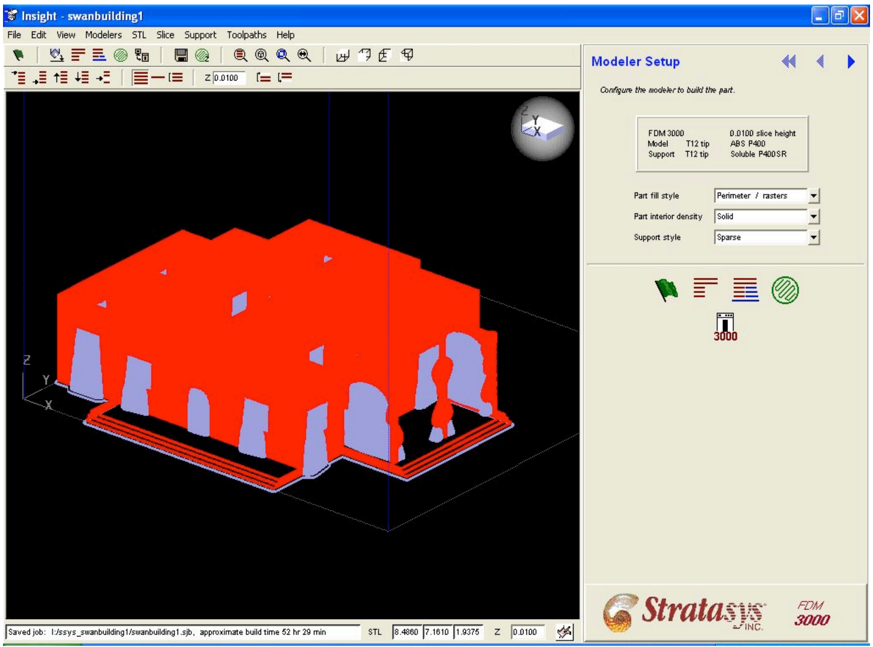

Figure 4: Processing in INSIGHT software showing supports material (blue)

2.2.3 Working in Insight Software Program

The STL "triangle" file is imported into Insight software. Firstly, we set the orientation in which we wanted the model to be built. Models seldom come into Insight in the correct orientation. The next step in this pre-processing stage is to consider the working envelope of the FDM 3000 machine which is 10'X10'X16', hence the need to scale down the model in software by using scale factor of 0.01 before export the model. We then sliced the model it into layers along the Z-axis, and constructed the supports structures. After creating slices and supports, Insight needs to create the tool paths needed to build the part, Insight then computes the paths it will take to build the part and supports and display them in the window.

2.2.4 Estimated Build Time

Using the Insight software, we can estimate the required to build the part by FDM machine. In this case, the build time is to be 54 Hours & 18 mins which is presented in figure 2. After full processing of the STL file, it is sent to FDM machine to build the part.

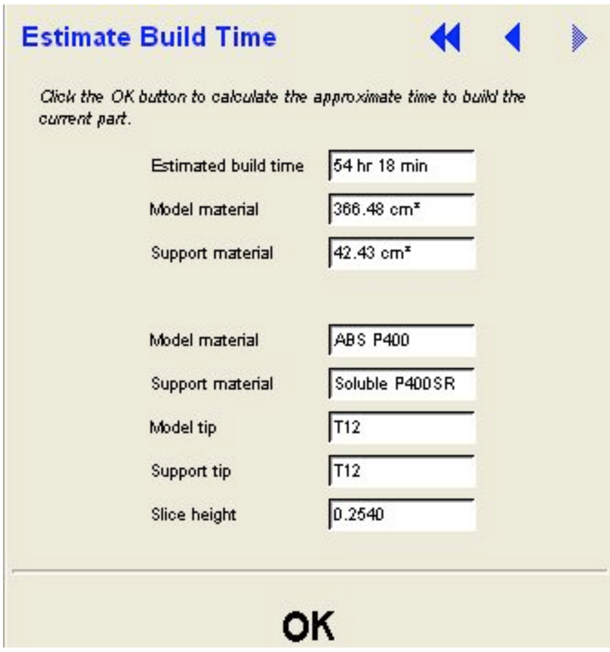

Figure 5. Estimated build time form

The main goal is to receive a prototyping quickly, accurately and cost effectively. Cycle time and cost can be then controlled according to the project requirements. The model and supports are removed. The surface of the model is then finished and cleaned, using an ultrasonic bath to wash away the unwanted support material. The University of Teesside is applying Rapid Prototyping Technology for teaching students about the new possibilities One example processed in University of Teesside is illustrated in Figure 6.

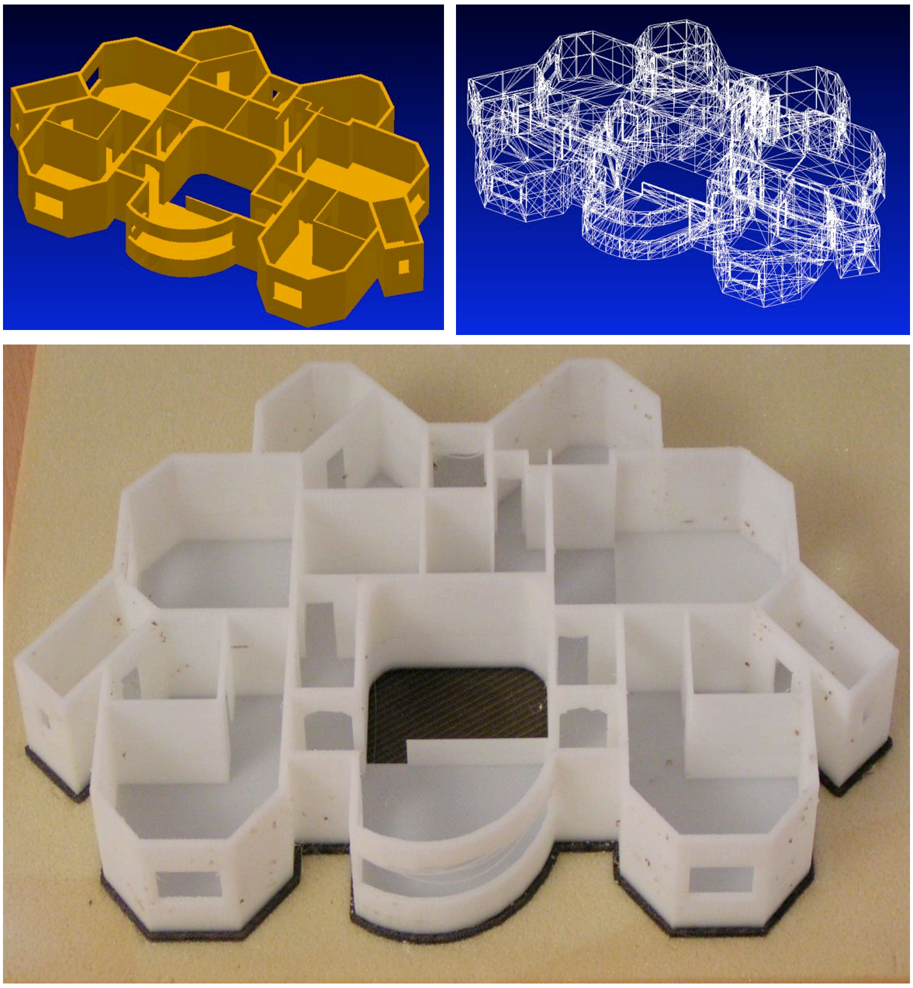

Figure 6: Derived from an EDS Ideas 3D CAD Model and manufactured on a FDM Prototype Model created on Stratasys FDM 3000 within hours at The University of Teesside

2.3 TRADITIONAL EXPERIMENTATION USING SUB-TRACTIVE METHODOLOGY CAM MACHINING USING DELCAM POWERMILL SOFTWARE

The same CAD model which we constructed using EDS I-DEAS-10 software program, in the STL "triangle" export format, was imported into the CAM software to simulate CNC machining, We started by defining the material block, the block defines the stock size. The part was to be machined from. We then specify Rapid move heights, The Rapid move heights are the heights at which the tool can move safely without hitting the part or clamps. The software automatically calculates the new tool Z heights based on the maximum Z heights of the block size plus the incremental Z heights. We then Specified Tool Start Point. The first operation was to perform a roughing area clearance (in 3D), a major strength of Power Mill is the range of area clearance options it supports, and the ease with which modification can be processed and viewed. The Area Clearance controls the tolerance, thickness, step-over, and step down value of the cutter as well as other machining options, We then performed another area clearance but this time using the finishing strategy with optimised Constant Z Finishing, . Power Mill processes the cutter paths.

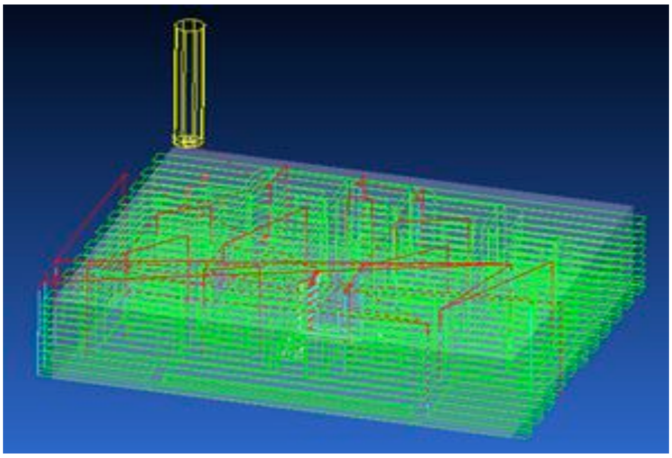

Figure 7: CNC Subtractive Machining: Cutter path simulation of 3D model

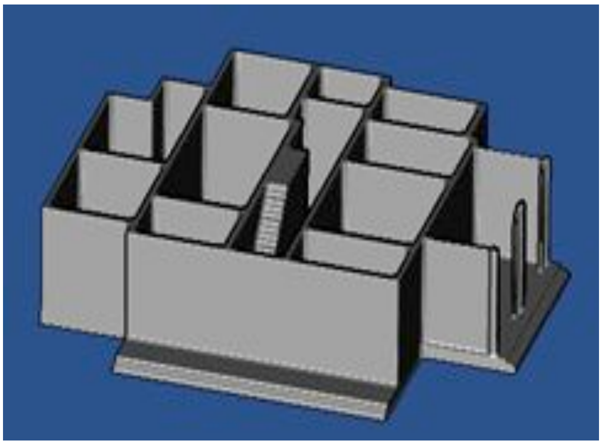

Figure 8: Result of CNC Machining with in DelCAM

Upon completion of pre-processing of simulating the machining we generated the NC code program (post Processing), the CNC program will consist of the number of blocks, tape length and total time

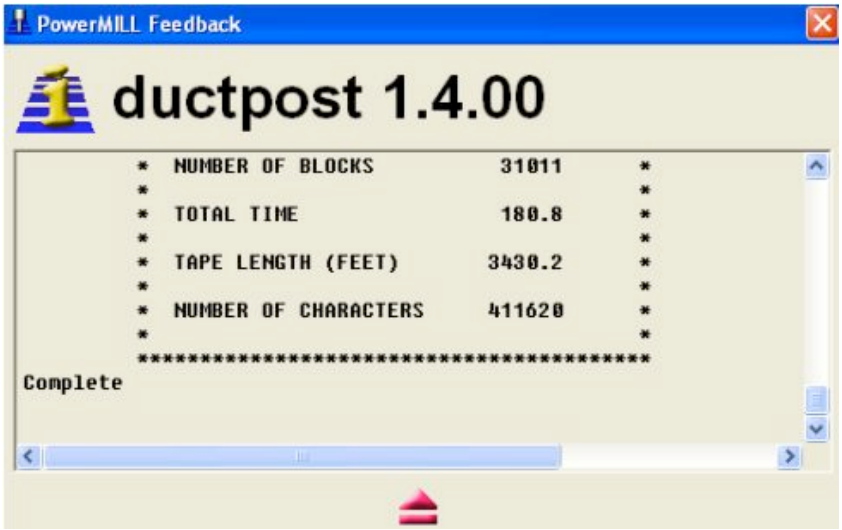

Figure 9: Feedback from Delcam

The Figure 9 shows that the intricate detail within the model will take longer to construct (machine), in order to achieve the same level of definition as Rapid Prototyping hence depending on traditional CNC machining to produce the architecture models is not the best way of the model making in this particular case, but we do stress this particular process is highly effective and desired for prototyping scaled curved landscapes, of larger sizes, as most RP machines would not be capable of producing models of a larger size.

3. Cost Comparison

First, a top-down approach is used to define the major steps involved in applying rapid prototyping. Next, a decomposition approach is used to itemize individual engineering steps involved at each stage. The approach calls for estimating labor hours, material consumption, equipment depreciation, and pricing of other work related to the rapid prototyping process.

- Cost Estimates related to 3D solid modeling
- Cost related to data preparation for solid freeform fabrication
- Cost related to part building

The research study shows the estimated build time by using FDM machine was 54 hr and 18 minutes and the necessary mount of materials which the machine need to build the part were: Model Material 366.48 minutes and Support Material 42 minutes . The spool of material consists of 475 per spool and the cost of the build material is £160 per spool and the cost of support materials is £135 per spool. A detailed calculation of the RP cost has been presented in Appendix 1.

As reported by Grimm (2003) "Build time is often cited as a measure of a system performance. While it is a key component in the total delivery time of a prototype, its value in a system evaluation is questionable", this also supported in this study from the third-party quotations that were obtained as shown in Table 2.

Whilst this study has used hourly rates during the evaluation, however, this is not seen as a viable measure of system performance or operational costs as observed by industrial analysts as reported by Grimm 2003. The costs used during this evaluation are based upon third party quotations, therefore the calculations have excluded capital and operational cost analysis, and hence are seen as a viable measure for this evaluation, and the results presented in this study.

In the traditional ways of architecture models, there is not a constant role to certain the total building time and cost. This method of modeling depends on the skill of the craft men to perform the job. However, an intuitive estimate has been carried out and presented in Appendix 1, Table A6. The cost has been compared in Table 1. The data presented are approximations only and are based upon our experimental figures, from personal assumptions. These figures for RP production may vary depending upon the number of components that may be nested into the build envelope as this would offer a more competitive advantage in pricing.

TABLE 1. Total building time and cost in each method of creating architecture models

S. NO	Method	Total time (Days)	Total Cost (£)
1	RP	3.63	1066
2	Traditional method	9.0	1475

Table 1 presents the total cost and time to produce the architectural model using traditional and RP techniques using FDM machine. From the data collection and analysis, it is found that using RP methodology is cheaper and faster than using traditional way of modeling. RP has many advantages, as it offers a quick turnaround in order to test, manufacture and market our idea as well as it is a way to make good quality of 3-D models and prototypes in a matter of hours, instead of weeks, from computer generated data. Also with prototyping our design idea can be created tested and refined quickly and economically, dramatically reducing product development time and improving our final result. Rapid Prototyping outside of mechanical engineering lie in architecture both as integral part of the design process and as a replacement for hand built models representing the final design prototypes. But one key problem in the case of architectural RP is the size to choose, because low cost RP machines are generally no longer than 250mm even the high cost RP machines are no longer than 500mm .

RP Technology is expected to be fast, easy to use, and cost effective that produce reasonable quality for concept modeling. The tests performed within this research found that FDM and CNC machining to satisfy these requirements, although CNC machining of the intricate details to models, led increased machine setup time and proved difficult in comparison to RP method. With its costs and operational demands, CNC machining and manual model making does not satisfy the time requirements when applied the study sample, typical of this industry application. Although research suggests that FDM RP method is time consuming in respect of build time, in comparison to its RP technologies such as 3DP and SLA. Table 2 presents a cost comparison to produce my model by using various RP methods, i.e. FDM, SLS and SLA..

Table 2: RP Cost Comparison Using Different RP methods (all in dollars), quotations obtained from www.quickparts.com.

Method	**Part cost with permitting finishing process**	**Part cost without doing finishing process**
FDM	-	$ 973
SLS	$ 775	$ 690
SLA	$ 1280	$ 973

As the research shows, the advantages of each model making method whether digital, manual or integration of both, the processes are dependant upon the application. Therefore when evaluating model making technologies, it is essential the specification of the intended application are clearly defined from the start. Grim 2003 stress that "It is important to identify the type of parts that will be prototyped. As seen in time, cost and dimensional accuracy data, results will vary with the size and geometric definition of the prototype". It is difficult to estimate and analyze the model making methods correctly as there are too many iterations associated to RP and CAD i.e. build parameters, prototyping materials, part definition, & different RP process technologies. Therefore the results presented in this paper are best suited for scaled models when similar parts are constructed with similar modeling parameters.

4. Some RP Modeling Issues Architectural Models

Results obtained from this research strongly demonstrate the importance of using information technology in the development of model making. The 3D CAD model replicas can be extremely accurate in dimension and geometrical shape, and digital methods can allow for simulation of properties, and improved visualization "such as walkthrough, and animations", which are give a better understanding "closer to the actual product". Complexity of geometry may be not be problematic within the CAD, however, these complex features such as undercuts and voids, can result in minor deformations in the prototype production, as shown in figure 10, these often result due to errors in processing rather than design i.e. incorrect machine temperature of the FDM Nozzle, in-adequate support material, unsuitable material for process/design. Consequently, with traditional manual model making there is a need to limit intricate features in order to fabricate a high quality replica. Hence, replica models with complexity will increase the amount of preparation required of the manual process and hence increase costs in terms of labor and skill base.

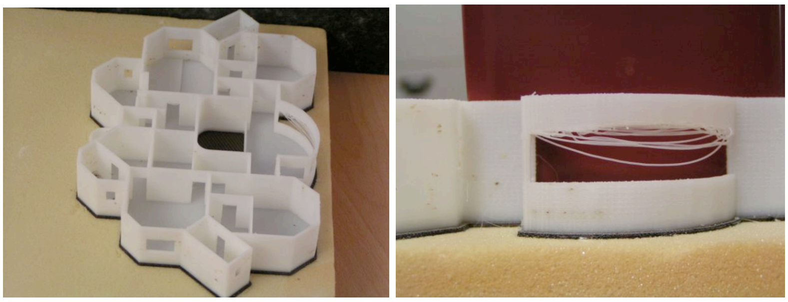

Figure 10: Errors in FDM RP Prototyping Process

5. Conclusions and Recommendations

Models help contractors, engineers, and architects in several different ways. A well-built model is a functional and informative tool intended to solve potential problems. Revisions in development and design can be derived from an accurately detailed model.

Models may be reviewed by all decision makers before construction begins. If modifications are required on the project, the costs of these alterations are much less before construction begins than during construction. Many times a model pays for itself many times over for this reason.

Plans in a 3D model form can be reviewed and more easily interpreted even by those who don't understand blueprints. A model can help people understand a complex project in minutes or even seconds. Time is more a factor in sales today than ever before.

RP offers the users the ability to present, negotiate, and market their ideas to the customers, thus they can modify their designs before manufacturing. Using 3D CAD systems adds more power to the design process, because it gives a complete idea about the final shape before starting the manufacturing process. As there is a pressure on companies to improve their products development performance, simulation and rapid prototyping will be commonly used to develop products faster, at a lower cost and with better quality, will help them to meet this objective. The findings from this study can be summarized as follows:

- A digital manufacturing method to produce prototypes of models is proposed and recommended in this research, by integrating rapid prototyping and CAD for architectural modeling requirements, a functional prototype model of a scaled building may be fabricated. Due to the versatility of RP and CAD, the integrated approach is exclusive as it creates opportunities to use materials with properties similar to those of the final products with respect of visualizations without the need for costly prototypes. Additionally, the use of an integrated process reduces the high costs often associated with using prototyping model making alone.

- An essential pre-requisite to use the RP technique is a 3D-CAD strategy for all parts produced using RP. The 3D-CAD models must fulfill the specific process requirements of RP techniques. This research demonstrates the major criteria associated with model making (RP or traditional) is the data preparation, and the understanding of the designer's concept. The requirement from the rapid prototyping perspective is to receive CAD data, which is free from clearance/interference, hence results in an appropriate structure of the activities in the model development process. In order to reduce the total development time by using RP techniques, data having the appropriate quality must be available far earlier in the development process. This means, contrary to today's process, significantly higher costs in the initial development phases. Further, the 3D-CAD strategy permits models to be verified in the computer, which up until now was an achieved using long introduction time where the modeling process was optimised. Using CAD techniques, simulation can also integrated into the overall process and earlier verification of CAD models can lead to costs being reduced in terms of design changes that maybe introduced at a later stage, but only prior to manufacturing commitment, in which case the related costs are similar to those associated with manual model making. Certainly, keeping the cost of labor and material down is a major concern in this research.
- Techniques regarding computer-supported evaluation of development results can be used in each phase of the product development process with different strategic goals. In this case, to use specific techniques, such as RP, in subsequent process segments, preliminary, up-front work is required to check development results using computer-based product specifications. In the aerospace-, automobile-, ship-building- and railway industries, projects are presently underway to define the next steps towards optimized product development using Digital Mock-Up (DMU) and RP.

This paper has reviewed the cost of producing architectural models by using RP and traditional way of modeling. By comparing the result, it is found that RP is cheaper and faster traditional way of hand modeling and it will save significantly the cost of model making in architecture.

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APPENDIX 1: Cost Calculation Details

Table A1: Total builds time by using RP techniques:

Data preparation for the building ground floor (hrs)	Design in IDEAS software (hrs)	FDM build time (hrs)	Post build operation time(hr)	Process to insert the data in INSIGHT software program (hrs)	Finish Process (hrs)	Total Time in RP (hrs)	Total RP Time (Days)
15	15	1	54.18	1	1	87.18	3.6325

Table A2: Total cost of using Rapid Prototype technique

Data Preparation cost (£)	Design cost I-DEAS (£)	Process to insert the data in Insight (£)	Build cost in FDM techniques (£)	Material cost (£)	Post build operation cost (£)	Finish cost (£)	Total Cost of Rapid Prototyping (£)
75	375	20	271	295	10	20	1066

Table A3: Time and Material Estimate for Traditional Model making

Design (hr)	Drafting in AutoCAD (hrs)	Model Creation/ Assembly time (hrs)	Finishing Process (hr)	Total Time (hr)	Total Model Making Time (Days)
15	7.5	37.5	7.5	67.5	9.00

Table A4: Cost of Traditional Model making

Design cost (£)	Drawing Cost in AutoCAD (£)	Material cost (£)	Finishing cost (£)	Model Assembling Cost (£)	Total Cost of Traditional Manufacturing (£)
450	75	50	150	750	1475