

Rapid Design and Manufacture Tools in Architecture

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Abstract

The continuing development of Rapid Prototyping technologies and the introduction of Concept Modelling technologies means that their use is expanding into a greater range of applications. The primary aim of this paper is to give the reader an overview of the current state of the art in Layered Manufacturing(LM) technology and it's applicability in the field of architecture. The paper reports on the findings of a benchmarking study, conducted by the Rapid Design & Manufacturing (RD&M) Group in Glasgow[1], which identified that the applicability LM technologies in any application can be governed by a series of critical process and application specific issues. A further survey carried out by the RD&M group investigated current model making practice, current 3D CAD use and current use of LM technologies within the field of architecture. The findings are then compared with the capabilities of LM technologies. Future research needs in this area are identified and briefly outlined.

Keywords: Architectural Modelling, Concept Modelling, Layered Manufacture, Rapid Prototyping, Virtual Prototyping.

1 Introduction

Many applications both engineering and architectural currently require complex 2D representations (drawings) coupled with models or prototypes to give both the client and the designer feedback on the design. This is true whether the product is an

engineering product or a building. Models allow those without an understanding of the information conveyed in 2D technical or building drawings to better understand the design and communicate design intent. In recent years great advances have been made in the capability of a new class of design tools; Layered Manufacture (LM) and Virtual Reality (VR). Commonly these two technologies are referred to as Rapid Design and Manufacture (RD&M) tools. Both offer a number of significant advantages over conventional modelling techniques such as speed and versatility. As both technologies require the availability of 3D CAD data before they can be used they have been instrumental in accelerating the move from 2D to 3D CAD.

The Virtual Design Institute (VDI) in Glasgow was established in 1997 funded by the Scottish Higher Education Funding Council (SHEFC). The VDI was set up on the basis of three distinct yet complimentary groups;

- Virtual Prototyping
- Virtual Environments and
- Rapid Design and Manufacture

The RD&M group has been constructive in establishing an RD&M Centre in Glasgow. As part of this work a number of studies are being conducted into the applicability of RD&M technologies in all sectors of industry. This fits in with the key research themes identified during the establishment of the Centre; the enhancement of current RD&M technology, the development of application methodologies for RD&M technologies in the product development process and enhancement of the information exchange and data management issues relating to RD&M.

The implementation of Layered Manufacture has been slow due to a lack of understanding on the issues involved especially in those industrial sectors not directly related to engineering such as architecture. This paper will set out to describe a number of key aspects;

- Current practice in Architectural modelling
- Current state of art in Layered Manufacture
- Discussion on the applicability of RD&M technologies in the field of architectural modelling.

2 Model Making and Visualisation in Architecture

In order to establish the role that LM has to play in architectural design practice a survey⁵ was conducted to identify a number of key aspects;

- Conventional model-making
- Current use of 3D CAD
- Time and cost issues and
- Existing use of LM technologies

The key findings of this survey were as follows;

- There are typically 3 levels of architectural modelling dependent on the stage of the design project;

⁵ Lewis Beck, ADF Partnership – Glasgow

1. Feasibility Model
2. Planning Model
3. Final Project Model

The first two levels of modelling are generally carried out in house using simple cheap materials. An individual within the company skilled in model making usually constructs these models. The final stage of modelling is usually carried out using an external model-making firm.

- 3D CAD is generally used for visualisation purposes where 3D Data can be rendered to give a simple indication of the form and mass of a building design. This data is also now used by some firms for Virtual Reality visualisation.
- The key characteristics of architectural modelling and visualisation are; Accuracy, Scale, Size, Time, Cost and Materials

2.1 Feasibility Model

The feasibility models are basic card and plastic models that give a client unfamiliar with 2D Data an idea of the form and mass of the building. They cost a few pounds (£) to produce and often only take between half a day and a day to complete. Accuracy is generally within mm's. Ordnance Survey map data is also used in a 2D format to give an idea of how the design fits in with the local infrastructure. These models are generally made in the architectural office using skills still taught at university. The models are fragile give an impression of form and mass and have low detail. The models are photographed and used in brochures presented to the client.

The equivalent of this model in the product design field would be the concept model. The picture in Figure 1 shows a feasibility model of a hotel development built using conventional techniques.

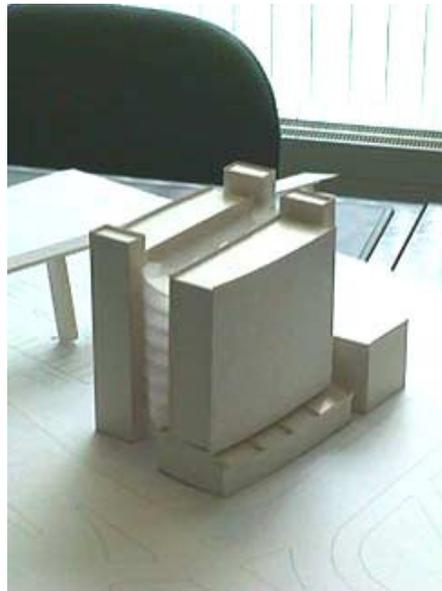


Figure 1: Feasibility model of hotel development .

2.2 Planning Model

This type of model is used at the planning stage of a project where a little more detail is required. The models costs no more than £50 to manufacture and are again generally made in-house. They take a little longer to manufacture taking around a week and again use materials such as paper, card and wood. The models are more robust and give a clearer understanding of how the building fits in with its surroundings. The models still only gives an idea of form and mass, textures are not added at this stage. Figure 2 shows a planning model of a shopping development.



Figure 2: Planning model of shopping development.

2.3 Final Project Model

The final stage in model making for architecture is the final display model that is used to show the public and clients how the development will look once the project is completed. They include topographic and texture information using plastics, fabrics and other more expensive materials to create as realistic a model as possible. This type of model is not made in house and is generally contracted out to a professional architectural model-making firm. The model of a leisure development shown in Figure 3 cost approximately £6000 and took almost four weeks to complete.



Figure 3: Final model of a leisure development .

As mentioned at the beginning of this section the characteristics of architectural models can be described using seven criteria; Scale, size, cost, time, materials, complexity and accuracy. These have been given in Table 1.

Table 1: Characterising the 3 levels of architectural modelling.

	Level 1	Level 2	Level 3
Scale	1:200 1:500	1:200 1:500	1:200 1:500
Size	250 x 250 x 250	250 x 250 x 250	250 x 250 x 250
Cost	£'s	£10's	£1000's
Time	Hours	Days	Weeks
Materials	Card, plastic	Card, wood,	wood, plastic,
Complexity	Low	Medium	High
Accuracy	Low	Medium	High

2.4 Computer Based Visualisation

With the continuing development of computer technology the use of computers for 3D visualisation of design data is becoming increasingly common. Even basic PC systems are now capable of producing photo realistic rendering of design data, Figure 4. An extension of this basic idea is the creation of 3D worlds that allow a designer to interact with their design, this field has become know as Virtual Reality. Virtual Reality has the potential to offer realistic virtual environments in which designers can see, walk through, touch and even change their design interactively before the 'product' has been made. This 'product' could be anything from a car, ship, aircraft or even a building. The real advantage of VR is the ability to model complex systems of components. This technology is still developing and a great deal of research is still required to more fully develop it's promised potential. The VDI is ideally placed to achieve this through the Virtual Environment Laboratory (VEL) in Glasgow.

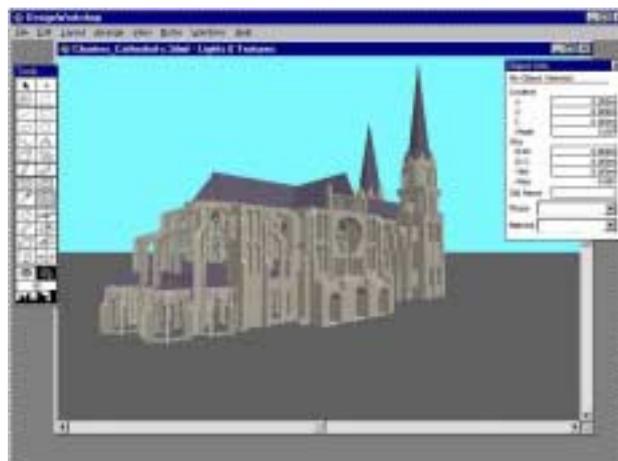


Figure 4: Simple PC based Visualisation



Figure 5: The Virtual Environment Laboratory

The VEL⁶ is an interactive immersive VR facility set up with funding from SHEFC as part of the VDI project mentioned earlier. This facility is powered by Onxy2 Silicon Graphics computer systems and a Trimentions projection system. Model data in the form of VRML models are projected onto a screen 5m diameter and 3m high. This facility is shown in Figure 5. It provides 160° vision for 15 people. The curvature of the screen gives users peripheral vision feedback giving them a feeling of immersion.

A number of projects are currently underway using this facility including the ‘Glasgow City Model’ [2] and the use of virtual models to look at disabled access to public building. Figure 6 shows one of the 3D worlds developed using the VEL.

⁶ Malcolm Lindsey, VEL – University of Strathclyde, School of Architecture.

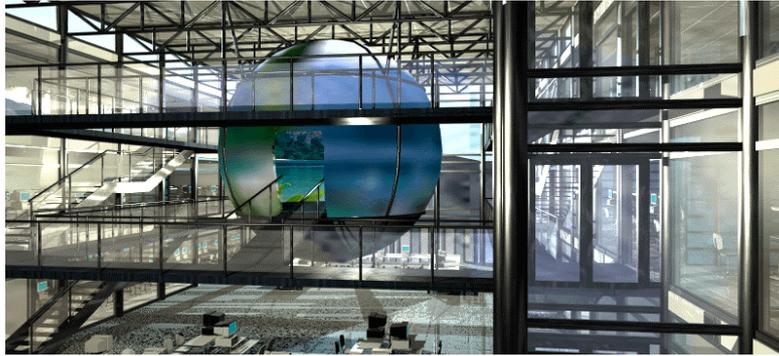


Figure 6: A Virtual Model

3 An Introduction to Layered Manufacture

The original term Rapid Prototyping was coined in the late eighties with the commercialisation of the first technology, Stereolithography marketed by 3D Systems. At that time Layered Manufacture technologies could only produce inaccurate visualisation models. Since that time the capabilities of these systems has developed until some machines are now capable of creating metal tooling accurate to within 0.1 mm. With the development of technologies such as concept modelling and Rapid Tooling the term Rapid Prototyping no longer describes the full scope of the technologies available. The term Layered Manufacture (LM) will be used throughout this paper to identify the group of processes that create 3D physical models layer by layer. The concept of layered manufacture is clearly shown by Figure 7, where 2D layers are created and stacked to form a 3D shape. The majority of LM processes differ only in the way in which they specifically create these successive 2D profiles. There are 3 strands of LM technology;

- Concept Modelling,
- Rapid Prototyping and
- Rapid Tooling [3].



Figure 7: A 3D Puzzle: the concept of layered manufacture.

As mentioned briefly in the introduction LM processes require that 3D CAD data is available before they can be used. The industry accepted standard 3D-file format for RP is the STL (Stereolithography) file format. Most 3D CAD systems now include an STL export capability.

All known RP processes can be grouped together according to the phase of the base material used in the process, either solid, liquid, gas or combinations of these. Figure 8 shows the better known systems available through either bureau services or for purchase in the UK. Detailed descriptions of these processes are given by Kruth [4] and Pham [5].

Liquid	Stereo-Lithography	3D Systems SLA	Aaroflex Solid Imager	Denken SLP	Fockele & Schwarze	NTT Data CMET-SOUP	Cubital Solider
	Fused Deposition Modelling	Stratasys FDM	Stratasys Genisys				
	Ink Jet Printing	3D Systems ThermoJet	Sanders Prototype ModelMaker				
Powder	3D Printing	Z Corporation Z402					
	Selective Laser Sintering	DTM Corporation SinterStation 2500+	EOS EOSINT (P/M/S)				
Solid	Laminated Object Modelling	Helisys LOM	KIRA Corporation SAHP	Kinergy ZIPPY	Schroff Develop. JP System 5		

Figure 8 : Process Characterisation according to phase of base materials used in the process.

3.1 Concept Modelling

With the development of 3D Printers a new field has been established within Fast Freeform Fabrication. The Concept Modellers offer the ability to produce physical 3D models quickly and at lower cost but with lower accuracy. There are currently three systems available in this category;

- The 3D Systems Thermojet 3D printer
- The Stratasys Genisys 3D Concept Modeller
- The Z Corporation Z402 3D Printer

3.1.1 The Thermojet 3D Printer

The Thermojet system uses the Multi Jet Modelling (MJM) process to build concept models in a low melting point thermoplastic material. Material is printed onto the current layer via a print head that extends across the build area, increasing the speed at which material can be deposited. Where overhangs are created they are supported

using a structure generated automatically by the software. Unfortunately this structure creates a rough surface when it is removed. The material is quite brittle and can be broken easily if dropped. The accuracy of the system is quoted at 300dpi in x and y.

Advantages: Fast Process, Office friendly, low initial and running costs

Disadvantages: Brittle Material, Limited range of materials, rough surface at supports.

3.1.2 The Genisys Concept Modeller

The Genisys Concept Modeller from Stratasys uses a process developed by IBM similar in operation to the FDM process described in the next section. A polyester material is extruded from an extrusion head and deposited in tracks or 'runs' onto the current layer. This process also requires support structures to support downward facing surfaces, these are generated automatically by the software. The material is quite robust for normal handling but could not be used for functional testing. The accuracy of the system is again quite low at about 0.4mm in X and Y.

Advantages: Fast, office friendly, robust materials

Disadvantages: Limited Materials, poor accuracy, poor surface finish

3.1.3 3D Printing (3DP)

The 3DP process developed by MIT throughout the 1990s was commercialised into a number of different systems, though only one the Z Corporation 3D Printer will be described here. In the 3DP process a water based binder is printed onto the surface of a powder bed to create the layer data. Because the binder is very low viscosity it can be printed in the conventional way and very quickly. Once the layer has been printed the powder bed is indexed downward a single layer thickness, a new layer of powder

spread over the previous layer and the process repeated until the part is complete. This process does not need supports as the powder surrounds the part supporting it. Once the part is finished it is indexed out of the machine, the excess powder cleaned away and the part(s) removed for post processing. In this process the parts out of the machine are quite weak and need to be infiltrated with an additional material. There are currently two infiltrates available; wax and epoxy resin.

Advantages: Fast, low running costs, office friendly

Disadvantages: Extra processing step required, limited materials



Figure 9: Concept Modelling Systems

3.2 Rapid Prototyping

Rapid prototyping technologies typically offer greater accuracy and a wider range of functional materials. They are more expensive to purchase and run, requiring dedicated production facilities. There are currently four main systems in this class, though there are others based on similar processes not discussed here;

- Stereolithography
- Selective Laser Sintering
- Laminated Object Modelling
- Fused Deposition Modelling

3.2.1 Stereolithography (SLA)[6]

Stereolithography was the first process to be commercially marketed in 1987. It is the most widely known and used with 37% of the market share.

In the SLA process each layer is created by selectively curing a photo-sensitive resin using an ultraviolet laser, Figure 10 shows a time exposure of a single layer being scanned by the UV laser. Once each layer is completed the build platform is indexed downward one layer thickness and the process is continued until all part data has been scanned. Because this process uses a liquid resin as the base material support structures are required to support downward facing surfaces. Once the part has been built it must be post cured in an UV oven to fully cure all resin in the part. Once this is finished the supports are removed. There is a growing range of materials for this process from humidity resistant to high strength and high temperature resistant materials, but they still cannot compete with some of the existing engineering plastics required by engineers.

Advantages; High Accuracy, medium range of materials, large parts possible

Disadvantages; high capital and running costs, 'messy' processes dedicated facilities required, requires supports, post cure required.

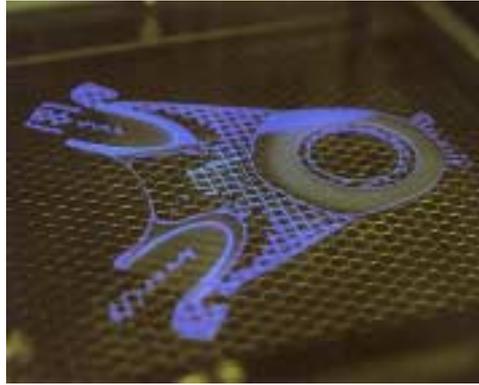


Figure 10: A single layer scanned in Stereolithography.

3.2.2 Fused Deposition Modelling (FDM)

Fused Deposition Modelling differs from SLA in that it does not use a laser to create the layer information. A filament of the build material is fed into an extrusion head (liquifier head) which is then heated just above its melting point. This material is then extruded through the tip of the liquifier head and deposited onto the parts as a run, a single strand of material, these 'runs' are extruded side by side to create the layer information. Once the current layer has been completed the build table indexes downward one layer and the process continued until the layer information is completed. Parts with downward facing surfaces require substantial supports, while as with most processes these supports are generated automatically though they do use up material. The material is an ABS plastic and parts built during the process have strengths up to 80% of the parent material. Other materials include; wax, medical grade ABS and an elastomer.

Advantages; good accuracy, functional materials, medium range of materials, office friendly

Disadvantages; Supports

3.2.3 Selective Laser Sintering (SLS)

The SLS process is currently one of the most versatile on the market, due mainly to the large number of materials available. In the SLS process powder is selectively sintered or melted by a scanning infra red laser source. Again once each layer is completed the powder bed indexes down by a single layer thickness and a new layer of powder is deposited and the process continued. As in the 3DP process no supports are required as the powder not sintered supports the part material. The surface finish of the finished parts can be described as slightly rough to the feel. There are currently seven materials available for this system including two tooling material options; Duraform (Nylon), Glass Filled Duraform, Fine Nylon, Trueform, Elastomer, Copper Polyamide, Rapid Steel and Sand Form materials.

Advantages; Large range of materials, good accuracy, large build size, tooling pathways.

Disadvantages; Dedicated facilities required, poor surface finish, curl/growth/Z+

3.2.4 Laminated Object Modelling (LOM)

In LOM the layer data is cut from solid sheet material using an infra red laser source. The material that does not form the current layer is “cubed”, cut into squares that will be removed by hand at the end of the process. Once each layer is completed it is bonded to the previous layer using a heat-activated adhesive. There is currently only one mainstream material in use for LOM, paper, though there are a number of other materials under development, plastic and composite. At the end of the process the part is encased in the excess material, which must be removed because of this the LOM process is best suited to large bulky parts that do not have intricate detail.

Advantages; Good accuracy, large build size, tooling pathways.

Disadvantages; Limited range of materials, poor material properties, support removal necessary.



Figure 11: Rapid Prototyping Systems

The capabilities and characteristics of the Layered Manufacturing systems described here are summarised in Table 2.

Table 2: Layered Manufacture Processes Summary.

	System	Max. Build Size	Accuracy ⁷	Cost ⁷	Time (hours) ⁷	Materials	Advantages	Disadvantages
Rapid Prototyping Systems	Stereolithography	508 x 508 x 600	0.1-0.2	£500 - £1000	10 – 12	Liquid Photosensitive Resins.	High Accuracy Medium Range of Materials Large Build Size	High Cost Process 'Messy' Process Support Structures needed Post Cure Required
	Selective Laser Sintering	380 x 330 x 420	0.1-0.2	£500 - £1000	10 – 12	Nylon based materials, elastomer, Rapid Steel, Cast Form, Sand Form.	Large Range of Materials Good Accuracy Large Build Size Tooling Pathways	High Cost Process 'Messy' Process Poor Surface Finish
	Fused Deposition Modelling	254 x 254 x 254	0.1-0.2	£200 - £300	10	ABS, elastomer and wax	Good Accuracy Functional Materials Medium Range of Materials Office Friendly	Support Structures Needed
	Laminated Object Modelling	813 x 559 x 508	0.1-0.2	£200 - £300	6	Paper.	Good Accuracy Large Build Size Tooling Pathways	Limited Range of Materials Support Removal Necessary Poor Material Properties
Concept Modelling Systems	ThermoJet	250 x 190 x 200	0.2-0.4	£100 - £200	2 – 4	Low melting point thermoplastic	Fast Process Office Friendly Low Running Cost	Brittle Materials Limited Materials Rough Surface finish on supported surfaces
	Genisys	203 x 203 x 203	0.2-0.4	Unkown (≈ £100 - £200)	Unknown (≈ 3 – 4)	Polyester based materials	Fast Process Office Friendly Robust Materials	Limited Materials Poor Accuracy Poor Surface Finish
	Z402	250 x 200 x 200	0.2-0.4	£100 - 200	2	Cellulose and starch powder, water based binder. Wax or resin infiltrates.	Fast Process Low Running Costs Office Friendly	Infiltration Required Limited Materials Poor Accuracy

⁷ Data from Layered Manufacturing benchmarking study carried out by the RD&M group in Glasgow. Based on a single part built in all technologies.

4 Matching Applications to Technology

The selection of the appropriate technology during the architectural design process can be seen to be dependent on a number of key issues;

- Cost and Time
- Model Requirements and
- Process Capabilities

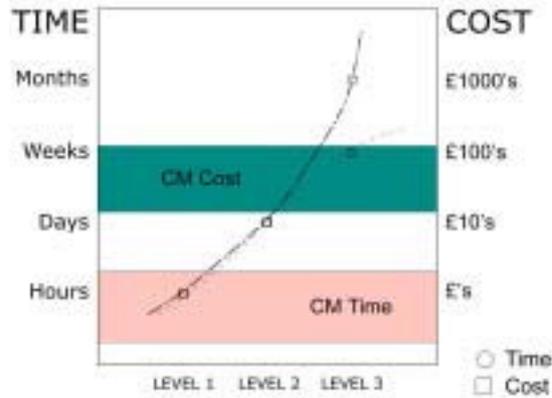
The discussion that follows will examine each of these issues in turn.

4.1 Cost and Time

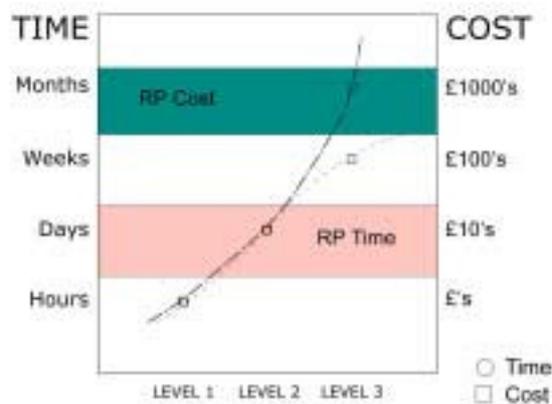
One of the main reasons that LM technologies are often not considered as a replacement for conventional modelling techniques is their high cost. In Figure 12a and 12b a comparison has been made of the cost of conventional technologies (i.e. hand modelling) against those of concept modelling and rapid prototyping. The cost of RP can be seen to be significantly higher than conventional modelling, while that of Concept Modelling is only slightly higher. It is the time taken to create the models however that makes these processes attractive to designers and engineers. RP models generally take 12-24 hours of build time dependent on the size and complexity of the model. Concept Modellers are significantly faster, models taking between 1 and 6 hours to build, again dependent on the size and complexity of the model. It should be noticed though that once the 3D Data is available the processes run automatically needing no operator intervention. In fact the concept modelling systems run in a design office environment in a similar fashion to a 2D printer. Rapid Prototyping is too expensive to be used at any stage earlier than the final modelling stage if this

technology is considered from a cost perspective only. In addition to this if the cost of the time taken by the architect making the models is taken into account then LM technologies become even more attractive. The cost and time comparison for VR shown in Figure 12c is included as a reference only.

Time and Cost vs Modelling Level
(inc. CM comparison)



Time and Cost vs Modelling Level
(inc. RP comparison)



Time and Cost vs Modelling Level
(inc. VR comparison)

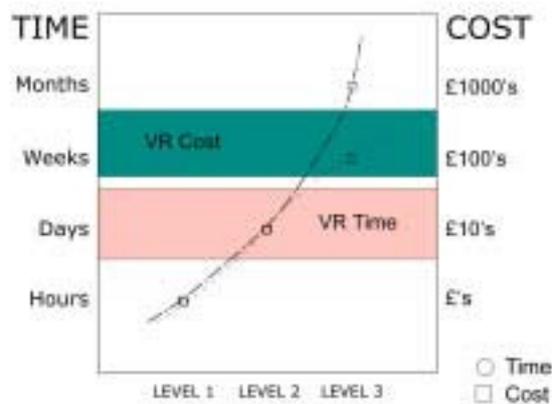


Figure 12: Time and Cost Comparisons for

- a) **Concept Modelling,**
- b) **Rapid Prototyping and**
- c) **Virtual Reality against conventional techniques.**

4.1.4 Matching Process Capabilities to Application Requirements

Each of the technologies discussed in this paper have their own advantages and disadvantages when used for a particular application. The characteristics of the models made using conventional technologies, Layered Manufacture and Virtual Reality are compared in Table 3.

Table 3 : Characteristic Comparisons for LM and VR against the 3 levels of conventional modelling techniques.

	Level 1	Level 2	Level 3	LM	VR
Scale	1:200 1:500	1:200 1:500	1:200 1:500	1:200 1:500	1:1
Size	250 x 250 x 250	250 x 250 x 250	250 x 250 x 250	Dependant on tech.	As modelled
Cost	£'s	£10's	£1000's	£100's - £1000's	£100's - £1000's
Time	Hours	Days	Weeks	Hours/days	Hours/days
Materials	card, plastic	card, wood, plastic	wood, plastic,	Polymers, paper	N/A
Complexity	Low	Medium	High	High	As Rendered
Accuracy	Low	Medium	High	High	As modelled

Physical models are generally better suited to applications where tactile feedback is required however these models only provide a snapshot of the design, if changes were made the model would need to be rebuilt. They are easily transportable and are not dependent on special hardware. They also allow large groups to continuously view the model. Physical models are built at a smaller scale than 1:1 for obvious reasons. As the models are scaled down some of the design detail could be lost. This must be considered depending on what the model is to be used for.

VR models on the other hand are better suited to interactive applications where visual feedback is required. They allow fly through visualisation in a 1:1 scale model of the design. They can also be used for simulation of thermal, safety or other factors within a building. The viewing of the model is however dependant on the availability of VR facilities. In some cases VR data can be viewed over the Internet using VRML. This is a powerful new tool for visualisation in distributed design projects. However in doing this many of the advantages of the interactive models are lost.

The speed and versatility of the LM processes makes them ideally suited for use by the architectural designer, though the cost has not yet reached a level to make this use widespread. With these technologies now available to the architectural designer a means of guiding the user through the technology selection process is required. One of the ways in which the inexperienced user can select the most appropriate technology is to use a selection database. There are a number of RP selection databases available. Most notable of these are those developed by BIBA[7] and Nottingham[8]. These tools allow the selection of a process based on the material requirements, speed, cost characteristics etc. At this stage though they cannot allow for other RD&M processes including Concept Modelling and Virtual Reality. They are also aimed more directly at the engineer not at other industries.

5 Conclusion

There remains a great deal of uncertainty concerning the applicability and role of both Layered Manufacturing and Virtual Reality technologies to a number of applications including architectural design. Many would argue that Rapid Prototyping remains too

expensive for use within the architectural modelling sphere. With the advent of concept modelling technologies, offering a greater level of speed and affordability, the range of applications is increasing. The ability to 'print' designs will greatly influence the way designers of all types from product designers to architectural designers conduct their design processes.

It is clear from this discussion that there is a great deal of commonality between the tools that should enable them to be used side by side to great advantage. The applicability of a particular technology to a particular application however is a complex issue that requires in depth understanding of a number of issues include cost, time-scales, model requirements and process capabilities. One way of making this simpler for inexperienced users of the technologies is to develop a tool that could guide the user through the selection process. This tool would be able to draw on a wide body of knowledge base of not only RP technologies but also concept modelling, hand modelling, computer visualisation and VR techniques. The research underway within the RD&M group in Glasgow focuses on the application of Layered Manufacturing technologies in conjunction with industry and academia and so makes it ideally placed to develop such a tool.

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