An Evaluation of Rapid Prototyping "Concept Modelling" Techniques for New Product Development

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ABSTRACT

Rapid Prototyping systems use layer technology to build physical prototypes directly from 3D Computer Aided Design (CAD) data. This provides the opportunity to design more complex parts and assemblies which cannot be made by existing technologies [1]. This paper reviews the emerging technology of low cost 3D printing techniques initially used for "concept modelling", to prove design intent and visualisation of these complex designs, but now being applied to end usage applications.

Concept modellers such as 3D System's ThermoJet, Z-Corp's 3D Printer, ObJet's Quanda, Stratasys' Dimension and EnvisionTec's PerFactory will be examined. A case study is used to show how these low cost systems can substantially reduce new product development time by their utilisation as production processes.

1.0 INTRODUCTION

1.1 Rapid Prototyping (RP) is a range of technologies which describe a process capable of creating complex physical parts directly from 3D digital CAD data [2]. There are now several commercial processes available, all of which work on much the same principle, ie layer manufacture, whereby the 3D digital part is sliced into many very thin layers that are then formed subsequently on top of one another to form the finished component or assembly. The use of RP is becoming more widespread as 3D CAD as a design tool is being used by small to medium sized enterprises (SMEs) to design and manufacture new products [3]. The advantages of RP over traditional CAM based tools are both time and cost of manufacture, ensuring the designer can hold a part designed yesterday in his/her hand today.

1.2 At the moment the RP industry is split into two distinct areas:

- High cost, high precision systems - SLA, SLS, FDM, LOM,
- Low cost (<£50k) "concept modellers" - 3D "Ink Jet" Systems
  - 3DSystems ThermoJet,
  - ObJet's Inkjet System
  - Z-Corps 3D Printer.
  - Other concept modelling systems
  - Stratasys FDM Dimension
  - Envision PerFactory

The high cost RP machines are predominantly situated in bureau companies with a range of machines to enable them to serve all their customer needs. The low cost RP machines are predominantly being installed in design houses and large OEMs to enable design verification and to serve as a communication tool [4]. Wohlers Associates estimates that 3D Systems, Stratasys, Z Corps, ObJet Geometries and EnvisionTec sold a combined total of 656 3D printers in 2002, compared to 490 in 2001. This is an increase of 33.9%. This jump compares to a decline of 4.3% in 2001. Growth of 3D printers in 2002 is an interesting topic of discussion, especially considering that sales of other RP systems grew by only 2.1%. 3D printers have grown to represent 25.8% of all RP systems installed worldwide [5]. This paper will review the current concept modelling processes and benchmark these processes. The paper will also investigate the application of the Z-Corps ZP400 3D Printer, and illustrate, via case studies, the use of the ZP400 RP process.

2.0 THE BENEFITS OF CONCEPT MODELLING TECHNIQUES

2.1 The principle of the "concept modellers" is that the parts are produced to a low accuracy of normally $\mp$ 0.5 mm, low part strength <15 M*Pa*, with limited engineering part utilisation. The benefits include:

low system purchase and operating costs, low part costs, load and go capability, and fast prototype part production.

However these “Concept parts” have been successfully used in several projects as parts, sacrificial patterns or tools for production of working components. A good example is the Z-Corps 3D printer binder cartridge head cap shown in Figure 1. This component is actually produced on the same machine that made itself. The ThermoJet uses a type of investment casting wax, and is now being used regularly in the production of aluminium and steel parts via the investment casting process without expensive new processes or process modifications at the foundry.

Figure 1: Z-Corps 3D Printer, Print head Cap

2.2 *RAPID PROTOTYPE SYSTEM SELECTION*

The selection of an appropriate, reliable RP system is an impossible task to fulfill to cover every prototyping requirement of a company. As most products comprise many different parts, which by their nature are manufactured from a range of materials due to the design intent. The selection of an RP system is a trade-off between total use of bureau services 100% to 0%, ie total production of all RP parts “in-house”.

Several RP systems can produce parts in a small variety of base materials. This is limited by the system process chosen and the amount of research effort that has been expended into the development of specific process dependant materials and process accuracy.

An analysis of typical parts requirements for a company is essential before even considering purchasing an RP system or systems. The key factors to consider are end part final material, part function, part size, accuracy, details, cost, security and speed, Figure 2 represents some of the decision branches that need to be followed when selecting an RP system.

Concept design is where the design is fully fluid and several concepts/ideas are being developed at the same time, as the optimum solution is not yet defined.

Concept modelling systems have been developed to provide designers with fast feedback on their work, and in order for this to be possible, the manufacture of RP parts for concept must be physically close to point of use. The parts need to reflect the intent of the designer in the form of shape and occasionally texture. They must also be quick and inexpensive in order that experimentation can occur freely.

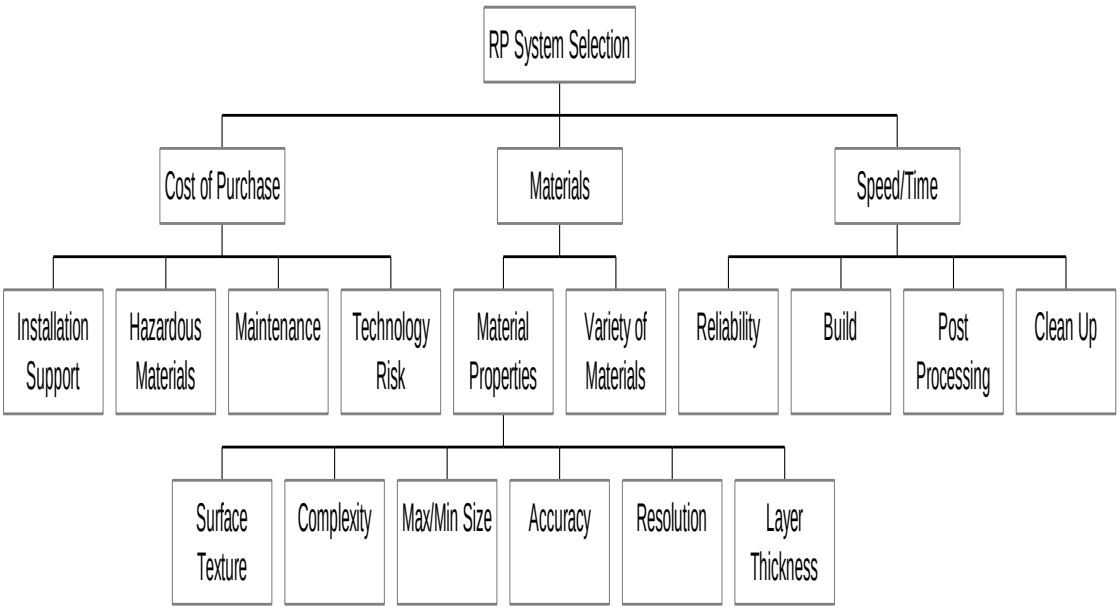

Figure 2: RP Selection Framework

3.0 REVIEW OF CONCEPT MODELLING PROCESS

3.1. 3D SYSTEMS THERMOJET SYSTEM

The MJM ThermoJet system [6] uses a print head to spray droplets of molten wax build material (also used as support material). The print resolution is 300 x 400 x 600 dpi (x, y, z). The process operates by first slicing the 3D CAD data into layers, these layers are then printed onto the layer below with several passes of the head required to deposit the full width of the component, Figures 3a and 3b.

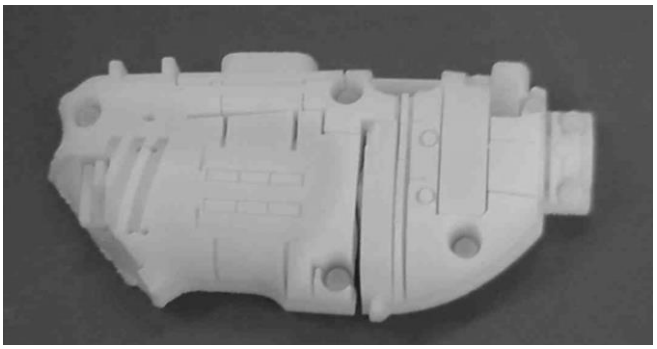

Figure 3a: Part from ThermoJet Process

Figure 3b: ThermoJet Machine
(Courtesy of 3D Systems Ltd)

A support framework is required for the underside of the components and any overhangs unconnected to lower regions of the model. The support removal is facilitated with the parts first being refrigerated to embrittle the support structure, this is one limiting factor of this process. Upper facing surfaces are capable of excellent surface finish detail, but underside surfaces are poor and the requirement for support removal means that wall thickness is limited.

Benefits	**Drawbacks**
Excellent for productive of investment casting waxes	Support material removal
Excellent upper surface definition	Brittle parts
Parts easily joinable via melting	Poor underside surface finish

Excellent upper surface finish	Not suitable for thin walled parts
Choice of two materials – ThermoJet™ 2000, 88	Reliability problems reported
Able to smooth models with heat gun or hot knife	
Supported by 3D Systems (largest RP machine manufacturer)	

3.2. OBJET'S INKJET SYSTEM

The ObJet system [7] was developed in Israel and uses similar resins to the SLA processes, i.e. it uses UV sensitive photopolymer. The process comprises the inkjet head traversing the build area, and where the part is solid, fine droplets of model material are deposited simultaneously with the support structure for future layers, Figures 4a and 4b. The resin is deposited with a print resolution of 600 x 300 dpi (x, y). A UV lamp situated above the build platform cures the resin droplets. The head has a y deposition width of 60 mm, thereby several strips of resin are laid for wider parts. The build platform lowers by one layer thickness (20 microns) and the process repeated. The parts are cleaned and the support structure removed by a combination of hand and water jet washing.

A second generation of ObJet machines have been released with fullcure™ materials with 16 μm resolution with eight print heads.

Figure 4a: Part from ObJet Process

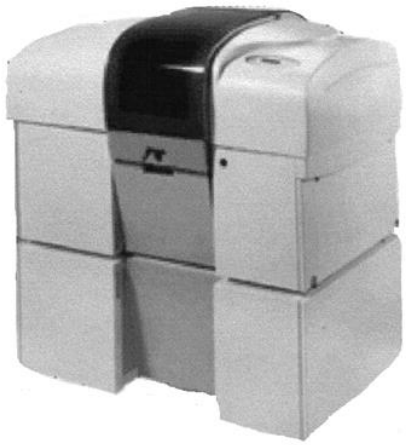

Figure 4b: ObJet Machine
(courtesy of ObJet Technology Ltd)

Benefits	Drawbacks
Material strength	Technology still under development – reliability, accuracy
Speed/width of build strip	New start-up Company
Similar to SLA resins	
Finest layer resolution (layer step) and print resolution (DPI)	
Form and fit testable	
Vacuum castable	
Two machine variants	
Large research and development budget	

Machines: ObJet Quadra Tempo, ObJet Quadra, Eden 330

3.3. *Z-CORPS 3D PRINTER*

The 3D printer is available in three machines. The basic build process is the laying down a layer of powder (ceramic or starch based) 0.1 to 0.25 mm thick. The model is sliced and the solid sections printed via "Canon InkJet cartridge" in the y axis, the carriage increments (similar to paper feed) in the x axis and another strip of binder is deposited. The parts are formed in the build chamber that drops by one layer thickness as more material is deposited [8] and bound above it, Figures 5a and 5b.

The machine is capable of building several layers per minute. As the powder supports the part no support structure is required therefore allowing complex parts to be built. The binder can be coloured with a dye allowing coloured parts to be generated, for example the results of a Finite Element Analysis. The surface finish on the underside is poorer than the topside due to seepage of the binder into the surrounding material [9].

A secondgeneration machine has recently been released based on a HP print head system, increase in accuracy and utilisation of Z-cast material for investment casting mould production

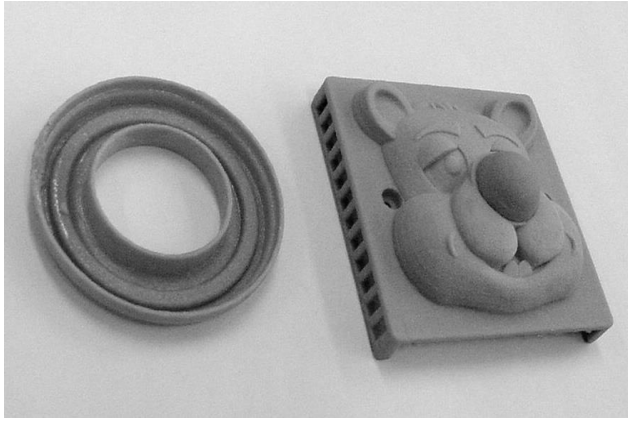

Figure 5a: Parts from 3D Printing Process

Figure 5b: Z-Corps ZP400 Machine

Benefits	**Drawbacks**
Fastest build speed	Least accurate of concept modellers
No support structure	Underside surface finish - poor
Complex parts, thin walled parts	Poor strength
Build materials :	Limited fit and function usage

starch - rubberising, investment castable
plaster ceramic - detail, definition strength
zircon - investment casting

New large build volume machine (largest of concept modellers)

Colour capable, Easy clean

Alternative powders – metallic, conductive

Machines ZP400, ZP406, ZP810

3.4. *STRATASYS – FDM SYSTEM*

Fused Deposition Modeller – Dimension – this is a re-packaged FDM 2000 system that uses ABS or wax filaments that are heated and extruded to form the part and support structure in the same way as the more accurate high end FDM machines [10]. The part is built on a foam base, and support structure and base removed by hand, Figures 6a and 6b.

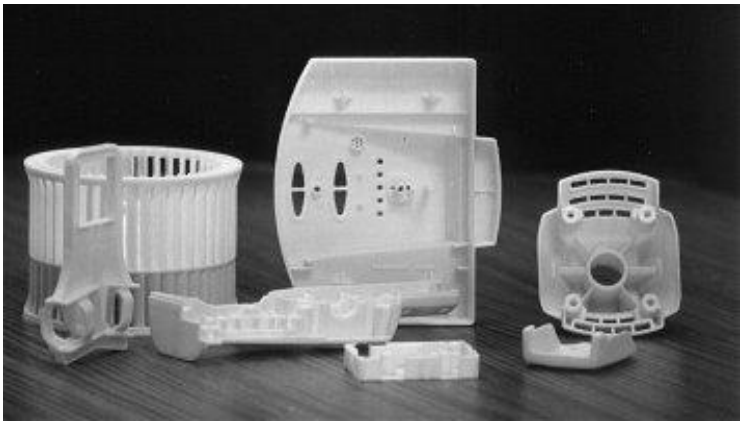

Figure 6a: FDM Dimension parts and Machine

Figure 6b: FDM Dimension Machine (Courtesy of Stratasys Ltd)

Benefits	**Drawbacks**
Material	Slow
Material strength	Expensive materials
Flexible hinges	Surface finish
Water proof	Finishing
Mature Technology	
Inexpensive - £23k	

3.5. *ENVISIONTEC - PERFACTORY*

Personal Factory – this is a new commercial process that uses similar technology to SLA in that light sensitive resins are set where the solid part is required.

The process is that of Stereolithography (SLA) machine in reverse, in that it builds the part from the bottom of the vat of photosensitive liquid and not from the top as in the SLA process. In place of an expensive laser, the Perfactory system uses visible light to set the resin [11].

The vat has a glass base, through which light is directed to set the layer of liquid resin above. The build platform tilts to peel the part from the glass and then lifts and squeezes a new layer of resin between the part and the glass, and a new layer is exposed, Figures 7a and 7b.

The light is projected onto the glass via an array of 1.25 million mirrors, each electronically controlled to shine a pixel of light upwards, or to deflect away from the build area. This Digital Light Processing (DLP) is the heart of the new technology (used in large screen projectors), and sets a layer in one process therefore saving valuable time. [11]

Figure 7a: PerFactory

Figure 7b: PerFactory Machine

Benefits	Drawbacks
Materials similar to SLA	New Process
Accuracy	Materials and process in early stage of development
Speed	
Inexpensive - £34k	

4.0 BENCHMARKING OF CONCEPT MODELLERS

4.1. The systems considered in section 4 have been benchmarked in Table 2. The processes are based on different technologies, therefore direct comparison of one to another is not possible. For example, the FDM machine has a vector manoeuvring system. Table 2 will assist companies in following their own specific decision path as per Figure 2, to ensure optimum process selection for their own individual requirements.

4.2.

RESOLUTION	Manufacturers' quoted accuracy – dots per inch or per mm of material laid down
ACCURACY	Relative from test work, observation and manufacturers' information 0 – lowest, 10 – highest relative to 3D systems SLA Viper System
DURABILITY	Relative to handling after post processing 0 – lowest, 10 – highest relative to 3D systems selective Laser Sintering process with 30% GF Nylon
SPEED	Time from receipt of STL file to part in hand, 0 – slowest, 10 – fastest, relative to Z-Corps ZP40x 3D printer
TYPICAL COSTS	Based on machine purchase price, speed of build, part build operation and material cost
COST	Includes installation, training and start up materials

Table 1: Justification for Table 2

4.3.

When relative criteria is used between 1 and 10 this is from user feedback and part inspection. (1 – lowest, 10 – highest.)

	3D Systems ThermoJet MJM System	Z-Corps 3D Printer ZP400/ZP406/ZP810	ObJet's InkJet Printer Quadra/Quadra Tempo/Eden 330	FDM Dimension	Envision PerFactory
Build Size (mm)	250 x 190 x 200	250 x 200 x 200/ 500 x 600 x 400	270 x 300 x 200	203 x 203 x 305	75 x 56 x 50 mini 255 x 191 x 250 std
Material	Thermoplastic wax	Starch, ceramic	Photopolymer	ABS	Photopolymer
Resolution (x, y, z) dpi/mm	300 x 400 x 600/ 0.08 x 0.065 x 0.04	300 x 300 x 360/0.08 x 0.08 x 0.07	600 x 300 x 1270/ 0.04 x 0.08 x 0.02	0.178mm(2)	0.07 x 0.07 x 0.03 min 0.25 x 0.25 x 0.5 std
Accuracy Relative (1-10)	5	4	6	6	7
Office Environment	Yes	Yes	Yes	Yes	Yes
No of build materials	Build material only	Power and Binder	Two – build & support photo-polymers	Build material only	Build material only
Support requirements	Yes	No	Yes	Yes	Yes
Date of Introduction	1998	1998/2000/2001	2000	2002	2003
Colour	Single neutral, grey black	Any single, colour upgrade/colour/colour	Amber (SLA colour)	White	Red
Durability Relative (1-10)	Brittle – wax 2	Brittle – plaster 2, Infiltrated 6	Good 7	Excellent 8	Average 5
Support removal	Yes – Refrigerated	No	Yes – Waterjet	Yes	Yes
Speed (1-10)	4	0	7	1	7
Material Recyclable	No	Ceramic – Yes, Starch – Limited	No	No	Yes
Medical models usage	Yes	No	Yes	No	Yes
Investment casting	Yes	Starch only – limited application	No	No	Yes
Bureau usage (UK)	Yes	No – In house	Yes	No	Not Yet
File type	STL	STL	STL	STL	STL/CLI
Support/Equipment	Fridge, technician	De-powdering unit, autowaxer (supplied)	Water jet washer	None	None
Typical costs per part (min costs may apply)	£20	£5 ceramic £10 starch	£30	£20	£15
Detail upper surface	Excellent	Good	Good	Good	Excellent
Detail lower surface	Poor – where supports removed	Average – Mottled underside	Good	Poor	Good
Expected Materials development	Improved strength thermoplastics	Metals, ceramics, carbons	Increased as per SLA process	None	Very Good
Cost	£36k	£37k	£46k	£23k	£34k
Maintenance (pa)	£5k	£3k	£6k	£4k	£3k
Start up Cost	£1.3k	£1.5k	£5k	£2k	£2k

Table 2: Benchmarking of Concept Modellers

5.0 CASE STUDY OF APPLICATION OF LOW COST CONCEPT RP MODELLERS FOR PROTOTYPE PRODUCTION

A local company approached the Centre for Rapid Production Development based at Northumbria University, after encountering problems with a new product they were developing. The function of the product was to produce the recess for electrical wall sockets, in a plaster/breeze block/brick wall. The product fits onto industrial impact hammer drills (with the drill action turned off); the component consists of a square plate with symmetrically arranged teeth in the shape of daggers, debris is allowed to fall between the teeth and out of the rear of the tool. The hole is produced by first drilling a location hole for the socket, the hole cutter is then located by this hole with a tapered extension, the cutter is aligned to the wall and 30 seconds of impacts occur. A furrow is then produced in the masonry, the tool is rotated 90 degrees and a further 30 seconds of impacts occur. The processes of furrow making and dislodging the brittle masonry in this pattern, rapidly makes the hole of the required size and depth even in very hard engineering bricks.

The problem the company was experiencing was that the hard brittle tool steel (D2) were found to be cracking and fracturing after limited usage (30 seconds). The company had been through the lengthy and costly process of design modifications, tooling modifications, wax pattern production and investment casting using traditional techniques several times. This cycle took typically 13 weeks from failure to new design concept, CAD design, tooling, casting and production of working prototypes. The public and their OEM's were losing faith in their product and their capabilities. To solve the problem, the CRPD and The CADCAM Centre worked together to redesign the cutter to reduce weight and critical stress concentrations by 40%. The FEA analysis however could not fully simulate the high-speed impacts and resonance, therefore physical prototypes were required as shown in Figures 8 - 10. Several sacrificial patterns were produced on the Z-Corps printer within the CRPD and successfully cast at a commercial investment casting foundry, which eliminated the tooling and wax production stages, therefore cutting 5 weeks off a 6 week process to get to the trial stage. The company now had D2 tool steel prototypes on test within a week of a new design being finalised and sent for RP production at 25%

of the cost previously paid. These sacrificial patterns are now being made using the ThermoJet process at the Digital Factory, Bishop Auckland College, UK, as this process is more tuned to investment casting than the Z-Corps process.

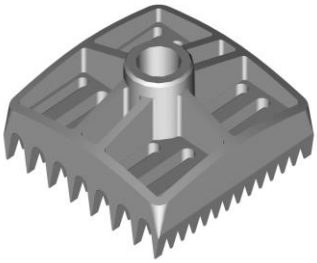

Figure 8: 3D model of design of square hole

Figure 9: FEA Analysis

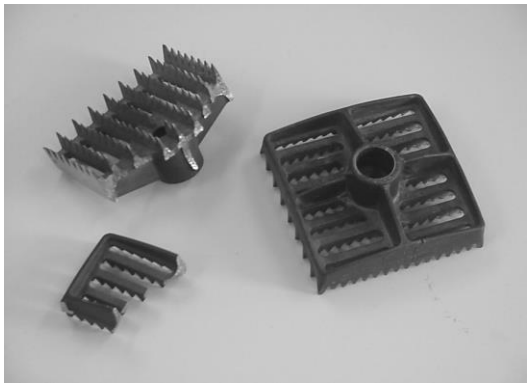

Figure 10: Original Casting and failed castings *(courtesy of Cleveland Engineering Ltd)*

6.0 CONCLUSIONS

The advent of mid range 3D CAD solutions capable of being used by Engineers as design tools, not just 3D modellers, has resulted in a requirement for rapid prototyping. Concept modellers as described in this paper can fulfil some of the design, test and evaluation requirements found in the product development process. The choice of which system is dependent on the end use of the parts produced. The ObJet process produces the most accurate and durable parts, the Z-Corps 3DP process the quickest, and the EnvisionTec process the most complex parts. The ThermoJet process is the most suitable for investment casting and excellent upper surface detail. The FDM Dimension produces the most usable parts due to the ABS mind material, but is the slowest process.

The PerFactory produces parts quickly with the material development along the SLA route this could replace some SLA processes.

The cost advantage of concept modellers discussed in this paper over traditional RP processes allows companies to create models as the design process progresses, allowing increased communication and participation of all stakeholders in the product development process.

7.0 ACKNOWLEDGEMENTS

The author would like to thank Government Office North East for providing the ERDF funding to support this project, together with the CRPD core team, Professor M Sarwar, Mr D Bell and Ms F Ward.

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