Abstract

The purpose of this study is to discover if Rapid Manufacturing (RM) is currently feasible for companies to invest in, and the possible impacts it could have on the design process. Rapid manufacturing is a modern production technique based on layer manufacturing from a computer-aided-design (CAD) model. A literature review has been carried out on current RM technologies, comparisons against injection moulding and the effect RM could potentially have on the design process. The results of which have been used to form a number of discussion topics, which have been analysed further through a qualitative approach. Leading experts in the rapid manufacturing field including company directors, suppliers, academics and technicians have been interviewed, and a case study has been developed from a company looking to implement rapid manufacturing techniques. The study revealed that currently rapid manufacturing has only been feasible in industries where the component price is high and the production volume is low. It was also discovered that businesses operating rapid manufacturing execute a significantly different design process in comparison to traditional methods, and a flow diagram of this process has been developed as a result of the observational studies.

HJC
DESIGN

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1.0 Introduction

The aim of this research is to assess whether businesses should be investing in Rapid Manufacturing (RM) at present if there are still further modifications to the process required. It is also the intention to identify the possible impacts that RM could have on the traditional design process.

The fundamental aims of this study are:

Aim 1 - To establish the current state of RM technology

Aim 2 - To establish the current feasibility of RM, and whether traditional manufacturing processes can now be ignored

Aim 3 - To investigate the potential affects RM can have on the design process

Aim 4 - To develop a RM design process model for prospective businesses

Aim 5 - To discover the future potential for RM

The study will be carried out by outlining the background and recent developments within the rapid manufacturing industry. A combination of literature investigation, naturalistic observational studies and semi-structured interviews will be utilised to enable discussion of the findings. The analysis of the discussion will provide outcomes to the research questions asked, and evaluate the current feasibility of rapid manufacturing for prospective businesses.

2.0 Literature review

In the world of manufacturing today, where competition is fierce, there is ever mounting pressure on businesses to meet the rigorous demands which the industry presents. Manufacturers undergo the challenge of supplying customised products with increasingly stringent lead times to meet the consumer's needs, and with increasing competition from the global economy, delays can result in business failure.

Current popular methods of production include injection moulding, vacuum forming, rotational moulding and milling, all of which have an extent of design constraints associated with them. These include the difficulty of removing parts from moulds, expensive tooling costs, long lead times, varying economic production quantities and large limitations on exterior form. These traditional manufacturing processes are also commonly subtractive, such as milling where a mass material is removed in order to produce the required geometry (Grenda 2007). An alternative approach to manufacturing and one which is gaining increasing recognition within the industry is Rapid Manufacturing (RM), where layers are used to build up the product through varying additive processes. This in turn can uniquely introduce design freedom, as without the restriction of removing a product from a tool, designers can theoretically be free to design any complex geometry that RM machines can be capable of making (Hague et al 2003). Further benefits such as zero tool costs, increased production efficiency and dramatically reduced lead times has meant that rapid manufacture is becoming an increasingly appealing technology for businesses.

Rapid manufacturing has evolved from the Rapid Prototyping (RP) technologies, such as Stereolithography and Laser Sintering (Anon, 2001). Time Compression Technologies (2000) have defined RM as "the use of layer manufacturing techniques for the direct manufacture of solid 3d parts, to be used by the end user either as parts of assemblies or as stand alone products". Layer manufacturing, or additive fabrication, enables the potential to use multiple materials optimising the component and its performance in ways not previously possible with conventional manufacturing methods (Grenda, E. 2007). Fig 2.1 gives a representative selection of today's major technologies used to make parts in specific classes of materials: (Sachs, E. 2001).

Plastic Parts	Metal Parts	Ceramic Parts
Selective Laser Sintering (SLS) -M3 Concept laser -RP3 Speedpart AB	Selective Laser Sintering (SLS) -Selective laser melting (SLM) -Electron beam melting (EBM)	Selective Laser Sintering (SLS) 3D Printing
Fused Deposition Modelling (FDM)	Direct Metal Laser Sintering (DMLS)	Fused Depotition Modelling (FDM)
Stereoligthography (SLA) -Jetted photopolymers -Spatial light modulators	3D Printing Sprayed Metal	Robocasting Stereolithography

Fig 2.1 - Overview of technologies used for rapid manufacturing (Sachs, E. 2001).

Research carried out by Hopkinson (2006) indicated that Selective Laser Sintering (SLS) is the leading rapid manufacturing technology to date, with Fused Deposition Modelling (FDM) and Stereolithography providing the majority of the remaining applications across the country.

SLS involves layers of powder being spread over a platform by a roller, and selected areas are sintered causing particles to melt and then solidify (Kruth, J 1994). Hopkinson (2006) expanded that the dominance of SLS is mainly due to the availability of a wide range of materials (polymers, metal and ceramics) and a superior accuracy and performance. An accredited midlands University and a prestigious UK car manufacturer illustrated the advantages of this technique by developing an 11 piece car door handle assembly comprising of eight material differentiations into a single material - a one piece component through SLS (Hopkinson et al 2005).

Since Computer Aided Modelling (CAD) directly drives all additive fabrication processes, it is theoretically possible to avoid the use of tooling altogether. Kotila et al (2001) utilised direct metal laser sintering (DMLS) in order to rapidly produce tooling, castings and small metal components. Grenda (2007) discovered that Rapid Tooling (RT) can dramatically shorten the fabrication time of high-value injection mould tools by as much as 30-40% in comparison to standard tooling procedures. Hague et al (2007) however has recently stated that no rapid tooling technology is yet capable of producing high volumes of parts because of a lack in material choice and inadequate production characteristics.

Furthermore, Mansour, S. (2003) revealed the ability to manufacture whatever shape is required may not necessarily give the complete design freedom and eradication of Design For Manufacture & Assembly (DFMA) that was initially perceived by Hague et al in 2003. There may still be a necessity to consider other components within a product and indeed the entire design process and its stakeholders. For example, there may still be the need to consider the assembly of components such as circuit boards, batteries and the capabilities and tolerances of the rapid manufacturing machine itself.

Despite the above suggestions, there are several success stories of rapid manufacture (RM) and its application within today's market. Steven Green (2006) identified the hearing aid industry as one of the first to apply RM technologies such as Selective Laser Sintering & Stereolithography for the mass production of personalised devises. Green (2006) reveals the design process utilises reverse engineering to produce a digitalised CAD model of the consumer's ear, then a sintered shell is created and electrical components are then housed into the part before the final finishing & testing phase. The CAD model can also help specialists give better counselling advice and increase customer satisfaction through a truly customised, unique part.

An investigation into a leading F1 racing team by Anna Kochan (2003) revealed that production SLS & DMLS parts were produced within twenty-four hours and their performance was then tested in wind tunnels straight from the machine. This enabled design iteration to occur more frequently and complex metal components could be created without difficulty. Phillip Delamore (2007) of a prestigious London College is currently developing the direct manufacture of custom made football boots using SLS, and sintered maxillofacial bone implants for the head and face are now available to all National Health Service (NHS) patients following research carried out by Gibson, I. (2006).

There is no doubting the scope and opportunities created through the implementation of rapid manufacture, but it has not yet been widely diffused into the industry with any great urgency. Massimiliano et al (2007) discovered that raw cost savings of up to 50% per component could be obtained by using rapid manufacturing instead of traditional injection moulding/tooling. However, the quantities surveyed (0-500) suited companies that were more akin to batch production or one off prototypes, and the break even graph developed by Dickens et al (2003) in Fig 2.2 further indicates that RM would become uneconomic at around 1000 parts.

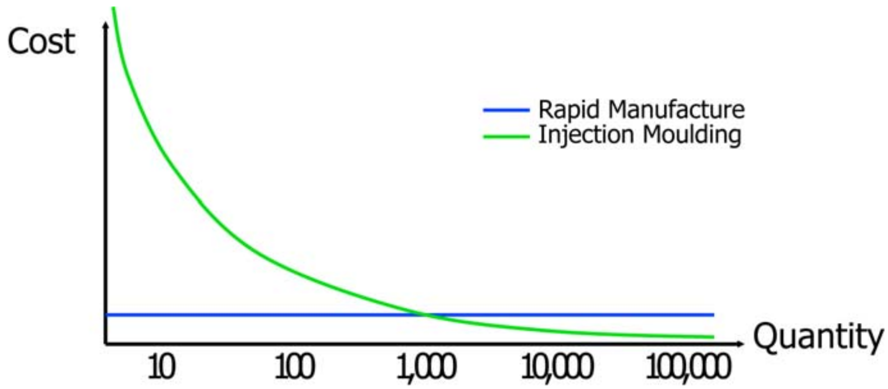

Fig 2.2 - A break-even graph to indicate RM and injection moulding production quantities against cost (Dickens et al 2003).

Conversely, Massimiliano et al. (2007) hypothesised that rapid manufacturing now has the capacity to produce further quantities and take advantages of economies of scale through the purchasing of materials and decreased process costs. A study carried out by Ruffo (2006) introduced a full costing technique for sintering production parts that included labour, materials, machine capacity, production quality and administrative overheads. The study revealed several significant cost & limitation factors overlooked by Massimiliano's (2007) cost model (mainly initial machine investment & build capacity) and highlighted that in the long term SLS would be more expensive and less feasible than injection moulding for companies demanding large quantity manufacture.

Maniscalco, R. (2003) identified such widespread opportunities for companies demanding small to medium size quantity manufacture and revealed that it could potentially lead to an era of products designed directly by consumers - creating new niche markets and demands for products created by the individual user, for their personal consumption. Dickens et al (2003), however, discovered such opportunities created through RM could have infinite changes on the design process within an industry. A favoured and conventional approach for the designer is to consider the stages ahead of design to try and eliminate any potential problems. Some factors that a designer may have to consider in order to eliminate iterations would be:

- Manufacture - Can the product be made with internal facilities?
- Sales - Are we producing a product that the customer wants?
- Purchasing - Are the parts specified in stock, or do we have to order them?
- Cost - Is the design going to cost too much to make?
- Transport - Is the product the right size for the method of transporting?
- Disposal - How will the product be disposed at the end of its life?

As a result of the nature of some companies, several areas of the design process may differ from industry to industry significantly in order to further fulfil their clients' and markets' needs within the timescale available. Dickens et al (2003) identified that stakeholders throughout the manufacturing chain such as logistics, outsourcing suppliers, operations & supply chain management could potentially incur drastic changes as a result of a company implementing rapid manufacturing procedures.

2.1 Literature review conclusions

A thorough background and context of the study has been established through investigation into a wide field of sources. As a result, the following statements have been raised to summarise the findings, and provide areas for further research to be addressed in the methodology.

- It is well documented that RM technology gives designers a wealth of geometric freedom
- Some academics foresee that RM will not totally eradicate DFMA, it conversely creates an off shoot - design for RM.
- There is huge potential for widespread customisation for consumers
- RT/RIM and RM are all battling to reach the same goals - rapid product manufacture
- RM could have a huge impact on the traditional design process
- RM is not currently widely diffused
- Resin technology is controlling the future for RM, but still doesn't give 100% performance characteristics of the 'real' material
- There are several core organisations documenting RM technology developments
- There is a break even point for RM and conventional tooling quantities, but with RM technology rapidly developing, there are contrasting views as to whether this exists.
- There is currently no documentation on the use of RM machines to produce high quantity, mass production parts
- There is no documentation on companies totally eradicating tooling and other manufacturing methods as a result of implementing RM
- There is no feasibility or design model for converting to RM techniques
- The future potential for RM is strong, but its application areas are unpredictable

3.0 Method

3.1 Procedure

The relevant stakeholders within the rapid manufacturing industry (suppliers, designers, academics and technologists) were interviewed in an aim to gather data on the following key topics that were raised from the literature review conclusions.

- The reality of designing with RM, and its impact on the design process
- The comparable quality and cost of end use part - injection moulding vs. RM
- Recommended quantities for current RM technologies - is the break even true?
- Have conventional manufacturing methods been totally eradicated since the implementation of RM
- The feasibility for current investment in RM, and which industry could benefit the most
- The future for RM

The question areas were chosen in an attempt to challenge some of the theory and knowledge gained through the literature review section and expand on topics that were found to have contrasting views among the published items. The questions aimed to focus direction and knowledge in key areas where there was previously a lack of information and published items available.

The investigation included the use of semi-structured interviews which involved the use of some prepared questions, supplemented by opportunities for the interviewee to expand the answer that has been given.

Q1. What is your current design process, and how has the implementation of RM affected its structure?

Q2. Is there a distinct difference between quality and cost between an injection moulded and rapid manufacturing end part?

Q3. What typical quantities do you produce to using rapid manufacturing?

Q4. Have conventional manufacturing methods been totally eradicated since the implementation of rapid manufacturing?

Q5. What is the potential for rapid manufacturing, and where does the future lie?

Interviews permitted the above complex issues to be explored, which are difficult to investigate through quantitative techniques that may lead to an oversimplification of the issues in hand. Interviewing however, allowed the precise exploration of the areas where other research methods present difficulties. Questions were also tailored to the responses of the interview such that issues could be explored where the research had not envisaged initially. Interviews therefore allowed flexibility in questioning and the possibility of uncovering perspectives unobtainable by other research methods. Field visits to the companies were made where possible so that the interviews could be held within the interviewee's respective offices in order to encourage a relaxed and friendly atmosphere. The interviewee was informed via telephone and email (see Appendix I) prior to the meetings that the trip was research orientated and a background to the study was also given in order to ensure the correct data was collected. The background explained that the interview would provide valuable information for a study into the current feasibility of rapid manufacture for today's businesses, with a comparison between conventional injection mould tool making and its design processes with the latest in rapid manufacturing procedures. The interviews were recorded via pen and paper on location.

There are however some certain limitations of the interview format. For example, misinterpretation or partial interpretation of data can take place, especially through pen & paper documentation. A particular problem associated with such interviews is that interviewees may be unable to put their thoughts precisely into words, and there may also be a difficulty analysing the data produced. Qualitative data obtained from unstructured interviews may not be easy to analyse. Inevitably, the potential for bias occurring in this reporting style is considerable, for example, researchers might only report certain aspects which support their own theoretical standpoint, or parts particularly relevant to their research which leads to a highly subjective selection strategy. To avoid this problem in the current investigation, it has been made clear the criteria used to select participants in the methodology section 3.2, and the interviews can be viewed in full in Appendix X. Whilst qualitative data generated by interview based research may add to the existing understanding, the interviews can also provide evidence that challenges theory of existing understandings - thereby stimulating further research and perhaps new theoretical perspectives.

Company D was used as a case study in this investigation which involved an intensive description and analysis of a single business. The data was obtained from several sources, including naturalistic observation, interviews and previous research conducted as part of a diploma of professional studies in 2006. Case studies provide a rich source of information about the particular area under investigation which in this instance is the manufacturing and design industry, and can be used to identify problems and design techniques for dealing with them. The information obtained through this approach was used to provide the basis for the design model of converting to RM, and further recommendations for the business.

3.2 Participants

The following companies and individuals were selected for their widespread expertise in the manufacturing industry. Their identities have been made anonymous for confidentiality.

Supplier A & **Client A**

Supplier A are the UK's first rapid prototyping & manufacturing supplier, and having had previous work experience with their technician it was decided that he would be able to help collect data and recommend contacts for further discussion. Supplier A also works with Client A whom were discovered in the literature review to be pioneering the use of RM to produce various parts in their formula 1 car.

Academic A

Having attended several RM seminars with Academic A it was decided that with many years of pioneering research and expertise of RM within the medical industry, they would be able to give insights into the current state & future for RM, the RM design process within the medical industry and its feasibility for current business investment.

Academic B & Researcher A

Academic B & Researcher A specialise in RM technology at a rapid manufacturing research group at an accredited midlands University. The research group is world leading in its field, and both experts have expertise in the future potential for RM and have a vast knowledge of currently unpublished research. Their specialist areas cover some of the unanswered questions in the literature review so were therefore a priority to consult.

Supplier B

Supplier B is best known for their activities in the field of rapid industrial and medical prototyping. They also have the largest capacity of rapid manufacturing equipment in Europe, and have a worldwide reputation as the leading software provider for innovative RM solutions. Their customer base includes all large companies in the automotive, consumer electronics and consumables sectors, and would therefore be able to give a broad and detailed insight into day to day use of RM, and its current implications.

Supplier C

Supplier C offer high standard services to clients in the field of rapid product development - a visit to their company based in Leicestershire was organised in order to gain a thorough knowledge of their design process from one of the countries leading RM subcontractors.

Company D

Company D is a fast moving Point-Of-Sale (POS) company with traditional injection mould tool development procedures. Having had a year's work experience at the company, first hand experience and observation of their design process has been obtained through previous studies and research. Company D provided a case study for this paper, involving a traditional manufacturing company with the hypothetical scenario of conversion to RM.

4.0 Results

The use of semi-structured interviews provided qualitative data that was analysed to see if any trends or similar answers existed. The data has been organised by question title, which increases the ease of identifying statements that contradict or concur between participants.

Key**:**

The prospective business - Company D - Director D - Blue Font

Supplier A - Technician A - Red Font

Supplier B - Director B - Purple Font

Supplier C - Director C - Orange Font

Client A - Turquoise Font

Academic A - Accredited midlands University - Grey Font

Academic B & Researcher A - Accredited midlands University - Green Font

Academic C - Accredited midlands University - Light Blue Font

:Q1. What is your current design process, and how has the implementation of RM affected its structure?

The prospective business - Company D - Director D

The design process employed by Company D, a dynamic fast paced point of sale design consultancy can be summarized into the following chain of events:

- Design meeting / Product Design Specification (PDS) - This is done to get a true understanding of the actual problem so a solution can be produced.
- Research

- Define Market needs
- Concept generation
- Concept selection
- Prototyping

  -Soft prototypes

  -Virtual prototypes

  - Hard prototypes
- CAD development
- Initial production - First run of production.
- Full production – After all problems of the initial production have been ironed out this is when mass production starts.
- Ongoing management - Capture, research and analyse new requirements; product releases, customer and partner service and support.
- Finalisation and hand-over
- Withdrawal

Supplier A - Technician A

- Company job/design process:
- Quote given same day
- Product specifications from designer
- 3d CAD - IGES/STL file formats
- File is analysed & verified - broken facets rectified
- Rapid tooling/Rapid Prototyping/Reverse engineering
- Post processing - e.g. surface finishing
- Functional & Ergonomic Tests

- Rapid Manufacture - begin production

Supplier B - Director B

- Large parts of complex products often milled in foam
- Simple products produced in the closest material for the prototype and testing.
- After a first milled synthetic prototype and different alterations in functionality, a set of vacuum formed models are made.
- In many projects, Stereolithography, SLS and Vacuum Casting used to discuss form, use, dimensions and functionality.
- Since prototypes are not functional, Cad software used to further analyse the product in order to reduce prototyping time - FEA performance analysis.
- Production begins

Academic A - Accredited Midlands University

Medical Design process for RM

- Patient data - Reverse engineering through CT scanning & bio models
- Surgical planning & bio medical engineer communication
- Geometrical Model - CAD/CAM engineer
- Design Evaluation - Bio medical engineer/medical doctor
- Production

Academic B & Researcher A

- RM has the ability to affect all parts of the manufacturing chain
  - Supply chain management
  - Logistics and distribution

- Outsourcing
- Design and product development

- Outsourcing for RM can be an alternative - exploit external supplier investments, innovations and capabilities
- Reduce operating costs and maintain focus on core competencies
- Different situations for companies who have existing knowledge base of RP and RM

Q2. Are there any distinct differences or limitations between an injection moulded and Rapid Manufactured end part?

Supplier A - Technician A

- Brittle surface appearance means Client A only use parts which give function and not aesthetic form
- Use a nylon powder that can give 75% performance of nylon 66
- Can produce parts overnight which withstand up to 150°C environments
- Supplier A use functional polycarbonate resins in stereolighography that give performance similar to ABS (Acrylonitrile Butadiene Styrene)
- Ideal for small parts as tool costs are reduced
- Use vacuum casting for small production runs
- Silicon moulds created from RP parts
- Vacuum casting gives colour solution - clear/rubber/glass/pantone colour

Client A

- Have used stereolithography for RP since 1987
- SLA gives many drawbacks - brittleness & lots of manual finishing - time consuming
- Now started SLS components - not a single mechanical failure as a result
- SLS components much tougher and durable
- SLS parts now replace many components made by other techniques
- SLS parts are very robust and could be used in a host of demanding applications
- Use SLS products for wind tunnel applications, brake blocks, mirrors & other exterior items
- Main benefit has been the production of mock ups from glass filled nylon and Alumide
- Alumide is a aluminium filled polyamide that can be milled and drilled
- On the current Client A mock ups, entire gearbox and most engine parts are produced by RM machines
- Electrical enclosures, wiring looms, cooling ducts and antenna housing further examples of SLS parts
- All Client A cars this season contain 20 non stressed SLS items
- Confidential component costs less than £1000 for each iteration, available in 2 days. Tooling the same component would cost £25,000 with a lead time of several weeks/months
- Confidential part cannot be used on the track, as material characteristics are not adequate - therefore tooling is still required.
- Strong benefits from shorter lead times from cad screen to reality

Supplier B - Director B

- Supplier B uses R.I.M. technology to produce small series of production parts.
- R.I.M. allows the production of small series of large parts at low cost in a very short time.
- R.I.M. suitable for the making of machine covers and housings, which have a considerable wall thickness and simple geometry.
- Large and small wall thicknesses can be combined without leaving sink marks and inserts can be encapsulated directly in the parts.

Supplier C - Director C

- Total tool manufacturing time up to the point of supply of sample mouldings for acceptance sign-off - 4 weeks.

Academic C

- DFMA is a principle to design for ease of manufacture and fabrication
- DFMA used to influence design in other areas - such as modularity, multiuse and multifunctional components.
- Injection moulding guidelines - draft angles, re-entrant features, wall thickness etc
- RM competes with injection moulding through tool-less production
- Considerations for wall thickness, flow of material, sharp corners, weld lines, sink marks, pins and draft angles no longer needed to be considered
- Reduce the number of parts within an assembly
- Part complexity and shapes produced by CAD can be directly translated to the product

- This is in essence, 'Design for Rapid Manufacture' - Design for SL
- Generation of detailed drawings can be removed - cad data directly produces parts
- Numerical controlled programming and tooling design avoided - previously very time consuming
- Limitations now set by Cad systems
- Internal components still geometry components - organic exterior forms not always suitable & desirable
- CAD may not give the spontaneity of the creative design sketch
- Large difficulty of interpreting the design intent
- Some design ideas not feasible with current software availability - geometric freedom not always true. Extremely organic forms not ideal for CAD and very time consuming
- Traditional tooling methods take longest part of production process
- CAD creation outweighs the production of the part - creates a bottleneck & requires extremely skilled personnel
- Major IPR issues combined with customer involved in designing custom built products with RM
- CE markings, quality control and ISO 9000 - 2000 conformance issues with consumers building parts themselves

Q3. What typical quantities do you produce to using Rapid Manufacturing?

Supplier A - Technician A

- 200-500 recommend suitable for vacuum casting - break even point for RM
- 10,000 or more recommend tooling

Supplier B - Director B

- A stereolithography prototype is made in Poly1500 - SLA used as master part for the RIM mould is constructed.
- Different mould types can be used for R.I.M; the selection of a certain mould type depends on the requested quality of the parts, the number of parts (lifetime of the mould) and their complexity. E.g., a resin tool with fibre reinforcement can produce up to 300 R.I.M. parts
- Lead time for parts around 3 weeks.

Supplier C - Director C

- Low volume RIM moulding system supplied Client B with production bumpers.
- Composite tooling system gives cost effective medium life (in excess of 500 off parts per tool), manufactured in a very short timeframe

Q4. Have conventional manufacturing methods been totally eradicated since the implementation of Rapid Manufacturing?

Supplier B - Director B

- Large parts of complex products often milled in foam
- Simple products produced in the closest material for the prototype and testing.
- After a first milled synthetic prototype and different alterations in functionality, a set of vacuum formed models are made.
- In many projects, Stereolithography, SLS and Vacuum Casting used to discuss form, use, dimensions and functionality.

Academic B & Researcher A

Example Case Studies

Firm 1 - no expertise & traditional production capabilities have the following options:

1 Manufacture in-house with existing equipment

2 Traditional manufacture & design

3 Outsource production to RM supplier

4 Purchase RM equipment and manufacture in-house

Firm 2 - RP or RM in house have the following options:

1 Existing knowledge base and some RM capacity from RP machines

2 Outsource decision based on cost and capacity factor

3 RP machines can be used if compatible with PDS - dependant upon product & cost

4 Typical quantities 1-500 off

5 No logistics

6 Stock holdings reduced

Q5. What is the potential for Rapid Manufacturing, and where does the future lie?

Supplier A - Technician A

- Use RM in wind tunnel testing & on production parts

Client A

- The future of RM is the integration of its term into rapid 'technologies', and make further advances into it becoming a conventional production technique.

Academic A - Accredited Midlands University

- Maxillofacial bone implants for the head and face
- Use SLS and mixture of polymer/ceramics/polycarbonates to recreate bone material
- Tissue engineering scaffolds - replacement organ development through cellular manipulation
- Invision tech use 3d printing to print living cells and produce living matter - "Bioplotter" - commercially available
- Medical industry awareness is poor
- Lack of expertise on the technology, and some surgeons are unaware of the availability of the RM/RP services
- There is an ethical need to educate patients and public awareness of the

treatments available through RM technology

- Expertise of surgeons dependant upon the NHS hospital and its location

Q6. Relevant Notes

The prospective business - Company D - Director D

- Traditional Production Quantities Discussion
- Trade off between CNC (Computer Numerical Control) and injection moulding with small volumes - dependant on individual job
- Volumes above 1000 on larger parts - create flat injection mould tools combined with fabrication
- 2000 or above fully tooled product

Supplier B - Director B

- After hardening, the moulded R.I.M. parts are finished and lacquered.
- Surface finish of the R.I.M. process permits a high quality painting.

Supplier C - Director C

- Client C supply CAD package data - Supplier C produce iterative designs for low volume production
- Supplier C supply on demand, fully assembled units directly into Client C to fulfil scheduled production build requirements.

Supplier B - Director B

R.I.M. Overview

- Extremely feasible for large parts
- Small lead times in comparison to traditional tool making
- Allows easy tool modifications and R.I.M. parts
- Cheap to manufacture in comparison to traditional tool making
- Produce items in a wide range of materials - thermal, electrical properties
- Significant wall thickness variations

5.0 Discussion

The information from the primary sources has added to the already documented knowledge. The research questions could now be analysed. **All citations within this section have been taken from the interviews unless otherwise indicated.**

5.1 The reality of designing with RM, and the impact on the design process

The literature review provided a background and focus to the topic, but due to the nature of the data required it was inevitable in a fast moving industry sector that a lot of the information was so far unpublished. It has been discovered that RM does have a profound impact on the way designers work, with Academic B revealing,

> *This (RM) is in essence, 'Design for Rapid Manufacture, or SL'. The Generation of detailed drawings can be removed since the cad data directly produces parts (…)*
>
> *The limitations are now set by the CAD systems.*

It is these limitations however that have always restricted CAD manufacture, with or without RM. It is well documented that CAD may not give the spontaneity of the creative design sketch, meaning some design ideas are not feasible with current software availability; extremely organic forms are not ideal for CAD and are very time consuming. It could therefore be suggested that ultimate geometric freedom (Grenda, E 2007) is only true to the extent of it being superior to existing manufacturing technologies. Furthermore Academic B adds,

> *Traditional tooling methods take longest part of production process (…) The introduction of RM now means that CAD creation time outweighs the production time of the part.*

If Company D were to take on RM their design process may have to change substantially, as it was discovered that the majority of time taken within product development are the creative & prototyping stages.

> - *Concept generation*
> - *Concept selection*
> - *Prototyping*
> - *Soft prototypes*
> - *Virtual prototypes*
> - *Hard prototypes*
> - *CAD Development*
> - *Initial production*
> - *Full production*

Conversely, Supplier B currently operate a heavily CAD orientated design process,

> - *Prototypes often milled in foam*
>
> *(…)*
>
> - *After a first milled synthetic prototype and different alterations in functionality, a set of vacuum formed models are made.*

- *(…) Stereolithography, SLS and Vacuum Casting used to discuss form,* *use, dimensions and functionality.*

- *(…) Cad software used to further analyse the product in order to reduce prototyping time - FEA performance analysis.*
- *Production begins*

Academic A also revealed a heavily CAD orientated design process within the medical sector,

- *Patient data - Reverse engineering through CT scanning & bio models*
- *Surgical planning & bio medical engineer communication*
- *Geometrical Model - CAD/CAM engineer*
- *Design Evaluation - Bio medical engineer/medical doctor*
- *Production*

Due to the lack of personnel operating CAD at Company D, it would create a large bottleneck if RM was implemented as most processes heavily involve CAD in some form, and may require further skilled personnel to be employed. Similarities can be drawn however between the two companies and their task details. For instance, there is still a need to consider design for assembly (the inclusion of non-RM components), design for maintenance, form & function, material properties and their characteristics. But with the ability to produce an end-use part rather than several prototypes, many stages of production can potentially be eliminated - going right to fit, form and function the first time around. These changes to the entire design process were documented by Researcher A,

> - *RM has the ability to affect all parts of the manufacturing chain*
>
> *- Supply chain management*
>
> *- Logistics and distribution*
>
> *- Outsourcing*
>
> *- Design and product development*

Proof of such a reduction in the design process and lead times was also evident at Supplier C where Rapid injection moulding systems were developed for Client C,

> *(…) Total manufacturing time up to the point of supplying sample mouldings for sign-off is 4 weeks.*

Taking into consideration the increased CAD development times and a reduction in other areas of the process tree, the industrial designer may be required to have more consideration of mechanical design and engineering. It could therefore be hypothesised that the advent of RM within a business, or industry could lead to a new breed and demand for unique, multi-skilled designers. Thus proving Dickens et al (2003) correct that RM does indeed dramatically change the way designers, and stakeholders work. Having taken into consideration the design procedures of the RM companies interviewed, Fig 5.1.1 indicates a prospective design process that Company D could employ if they were to introduce rapid manufacturing into their company.

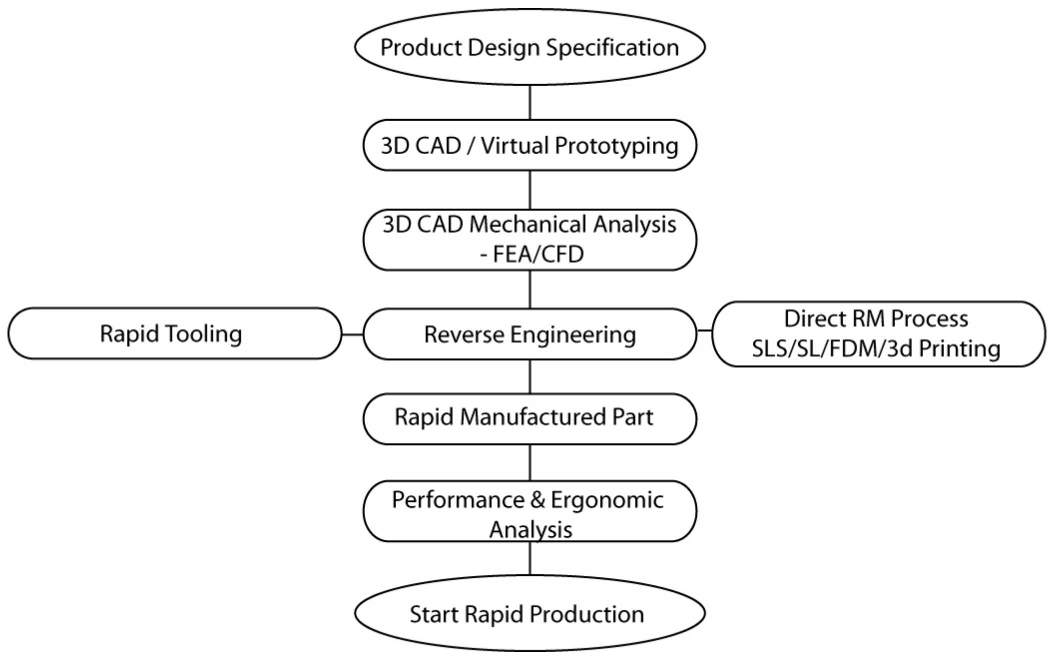

Fig 5.1.1 - Flow diagram to illustrate the Rapid Manufacturing design process for prospective businesses.

The flow diagram in Fig 5.1.1 indicates a CAD dominant design process that has been generated by analysing the procedures of today's leading rapid manufacturing companies. Its fully digitised and virtual processes reduce the need for physical prototyping, and enable further design iterations to occur before committing to a rapid manufactured part. This diagram could provide a structure to prospective businesses such as Company D in order to help them survey their current employee and company structure, and analyse the extent of impact that RM could have on their own design process and its stakeholders.

5.2 The comparable end use part - Injection Moulding vs. RM

Grenda (2007) makes a strong case that material and resin development has come a long way, and that a broader range of materials and material properties are now available which now include metals, plastics, ceramics and composites. Technician A expands,

> *Supplier A can now create a nylon powder that can give 75% performance of nylon 66.*
>
> *(…) we can produce parts overnight which withstand up to 150deg C*
>
> *Laser prototypes are available that use functional polycarbonate resins in SLA that give performance similar to ABS*

Client A also praise the benefits of SLS resin development,

> *SLS parts now replace many components made by other techniques*
>
> *(…)*
>
> *SLS parts are very robust and could be used in a host of demanding applications*
>
> *(…) the main benefit has been the production of mock ups from glass filled nylon and Alumide, which is an aluminium filled polyamide that can be milled and drilled*
>
> *(…)*
>
> *On the current Client A mock up, the entire gearbox and most engine parts are produced by RM machines*

On the other hand Technician A revealed that, *"brittle surface appearance means Client A only use parts which give function and not aesthetic form"*. Hence despite performance and cost benefits documented by Grenda (2007), direct RM technology can currently only support a small spectrum of materials for manufacture, of which products are manufactured for function rather than form. This is further evidenced by the RM product examples given by Client A,

> *(…) electrical enclosures, wiring looms, cooling ducts and antenna housing.*

Such primary application limitations of RM could be the major factor as to why rapid manufacturing is not being adopted by more companies. It is still apparent that the availability, material properties, cost of resins, accuracy, surface finish and part size are a core restraint to even the most pioneering of RM companies. Academic A expanded,

> *The medical industry awareness of RM is poor. There is a lack of expertise on the technology, and only some surgeons are aware of the availability of the RM/RP services. There is an ethical need to educate patients and public awareness of the treatments available through RM technology.*

Further knowledge and widespread awareness from the manufacturing industry may help drive the technology further and overcome these primary obstacles. The impact of rapid manufacturing has the potential to change every discipline in manufacturing, and the fear of obsolescence from traditional manufacturing companies may also be a factor in preventing rapid manufacturing from widely diffusing. However, upon assessing the RM break even graph generated by Dickens et al (2003) and the performance constraints mentioned above by Supplier C & Client A, it appears that the injection mould tool industry may not be under immediate threat from RM.

5.3 Recommended quantities for current RM technologies

A 'made to order' procedure would not be economically viable for a supplier or client prior to the invention of RM. Maniscalco (2003) idealises the possibilities of RM may lead to an era of products designed directly by consumers, creating niche markets for products created by and ordered by individual consumers. However the true test for RM is at the other end of the spectrum - whether it's mass manufacture qualities can rival other traditional techniques. Supplier C revealed examples of their quantities for Client C,

> - *Produce engine bay package and engine performance parts for MG Rover*
> - *Client C supply CAD package* data - Supplier C produce *iterative designs for low volume production*
> - *Supplier C supply on demand, fully assembled units directly into Client C to fulfil scheduled production build requirements.*
> - *Composite tooling system gives cost effective medium life (in excess of 500 off parts per tool), manufactured in a very short timeframe*

Supplier C's 'made to order' quantities are still in their relative low 1000's in comparison to injection moulding production volumes. The characteristics of rapid mass manufacture could therefore be described as 'staggered mass production', with Supplier A also adding,

> *Rapid manufacture is ideal for small parts as tool costs are reduced. Quantities of 200-500 are recommend, a typical break even point for us is around 5,000. (…) any more volume and we would recommend tooling.*

The quantities suggested by Supplier A and Supplier C provides support for Dickens et al (2003), in that the maximum economic quantity for RM currently lies at around 1000 off parts. Therefore with today's technology it may be best to consider and utilise rapid manufacture as a process for creating a broad range of diverse products balancing desirability, performance, costs and production volume. On the other hand, an entire production run over several years could include short-runs of 1,000 to 5,000 parts - suiting both RM and conventional aluminium machined tooling. Decisions may then be down to the manufacturing flexibility of the company and their preferences for tooling on short-run production. For a prospective company such as Company D, it may therefore be beneficial to analyse their product range and decide upon its diverseness, suitability, quantity and feasibility for justifying rapid manufacturing techniques rather than injection moulding.

5.4 Have conventional tooling methods been totally eradicated since the implication of RM ?

In contrast to Academic A and Supplier C, Supplier B do not solely rely upon rapid manufacturing to produce their prototypes and end use parts,

> *(…) prototypes of large parts of complex products are often first CNC milled in foam. Simple products are produced in the closest material for the prototype and testing. After a first milled synthetic prototype a set of vacuum formed models are made (…) and production begins*

Therefore despite a heavily CAD orientated design process, Supplier B still utilize traditional manufacturing and model making techniques to produce items at some stage in their design process. This suggests that it may be totally unreasonable to be solely dependant upon rapid manufacturing techniques to produce the entire product range for a company, and perhaps a combination of conventional and modern processes would be favourable in order to satisfy the product portfolio most efficiently and cost effectively. In addition, with much of manufacturing today being process-oriented, any quick change toward rapid production may also put production output in immediate jeopardy. With factors such as size, quantities, capacity, limited material range - it is increasingly evident that design for rapid manufacture has more parallels to Design for Manufacture & Assembly (DFMA) than previously hypothesised by Mansour, S. (2003).

5.5 The feasibility for current investment in RM, and which industry could benefit the most

Sachs (2001) describes the nature of RM production being based on additive production, with parts being able to be built simultaneously on a single machine. This could potentially provide a drop in cost for parts of increased volume as the costs of production would be split between the multiple of components within the build envelope. As a result, small manufacturers may be able to benefit the most from RM given the quantities of production as recommended by Supplier A,

> *Rapid manufacture is ideal for small parts as tool costs are reduced. Quantities of 200-500 are recommended.*

Small manufacturers are extremely limited in their methods of fabrication by the cost of tooling which must typically be amortized over a small number of parts. Director D of Company D expanded on quantity issues for the firm encounters in depth,

> *There is a difficult trade off between CNC and injection moulding with small volumes. Depending on the time it takes to CNC, we usually chose to fabricate, unless volumes are above 1000 on larger parts - where we would then look at creating flat injection mould tools combined with fabrication, and 3000or above would be a fully tooled product*

With the intervention of RM at Company D, such small products runs could be made without the use of injection moulding machines or tools, and would also provide an economic impetus for many smaller companies producing a similar product batch volume to become involved with RM. Furthermore, Sachs (2003) reveals that RM may give the possibility to fabricate products as complete assemblies reducing labour content. This would help reduce the costs of small production runs and increase flexibility further more, with Supplier C currently operating a similar procedure,

> *Supplier C produce on demand, fully assembled units directly into Client C to fulfil scheduled production build requirements.*

This suggests that it may no longer make economic sense for companies to export manufacturing jobs to different suppliers, with the most economical solution being to fabricate products nearest to the point of use. Fully assembled products may give many advantages such as reduced lead times, increased supplier relationships and the irradiation of assembly costs. However further administrative costs may be incurred in other areas - reduced time cycles and higher volumes of finished parts and deliveries will put further demands on the existing labour force and stockholdings, which may mean an expansion of manufacturing capacity is required. In addition, relying on a single supplier or machine to produce a complete assembly could have many business risks involved. Single supplier dependency may magnify the impact of machine down time on a company, which would affect delivery schedules and product launches - voiding any lean production principles in operation.

5.6 The future potential for RM

Until the properties and performance of the RM materials can rival the thermoplastics that are currently used in injection moulding and vacuum forming, additive fabrication may have limited applications within the product design sector. It is clear that Maniscalco's (2003) prediction for mass customisation has not advanced significantly in the past 5 years in relation to the product design sector, with only several UK companies such as Supplier B, Supplier C and Supplier A utilising RP machines specifically at rapid manufacturing applications commercially in 2007 The last hurdle for the implementation into product design applications may therefore be the speed of the systems using such new materials and the capacity of the throughput for the entire process.

However Academic A reveals in his interview that RM technology can be applied to produce three-dimensional tubes of living tissue via printers filled with suspensions of cells instead of ink.

> *Invision-tech use 3D printing to print living cells and produce living matter - "Bioplotter", which has now become commercially available in 2007*

Academic A also expands upon "*maxillofacial bone implants for the head and face via the use of SLS machine's,* and *"tissue engineering scaffolds that replacement organ development through cellular manipulation"*. Such work could potentially be the first step towards printing complex tissues or even entire organs. Thus revealing that rapid manufacturing may have a large scope for applications in areas beyond product design, which may well be where its characteristics can be best utilised in the future.

6.0 Recommendations for further study

It would be interesting to develop a case study further by following a company through their switch from traditional manufacturing process to an RM based production line - utilising the RM design process model generated in this study. Existing theories could either be supported or challenged by this investigation and could advance the thinking by providing a counter instance. Although results of case studies are not used to provide conclusive evidence, they can provide important evidence in support of or against a particular theory. There are various difficulties with this approach however. Firstly it would have to be a longitudinal study as the process of converting a business to RM may take considerable time. Researchers may also not be able to make valid casual inferences using the case study method because extraneous variables are not controlled and several developments alongside the RM conversion may be occurring in the company simultaneously. But overall, the study would provide an opportunity to study the implementation and development of the process and its outcomes on the company's product portfolio and resultant value index.

7.0 Conclusion

Aim 1 - To establish the current state of RM technology

The current state of RM technology has been analysed, and it has been discovered that Selective Laser Sintering (SLS) is currently the most popular process in today's rapid manufacturing industry, followed by Stereothigraphy (SLA) and Fused Deposition Modelling (FDM). Direct Metal Laser Sintering (DMLS) enables Rapid Tooling (RT) and Rapid Injection Mould (RIM) development, leading to reduced lead times and development processes. However, despite recent resin development offering the performance characteristics of Nylon and ABS, it will take many more technological advances and time before the library of materials available to rapid manufacturing is remotely comparable to those available to standard manufacturing technologies such as injection moulding.

Aim 2 - To establish the current feasibility of RM, and whether traditional manufacturing processes can now be ignored.

It is clear through the investigations conducted that rapid manufacturing has tremendous potential in low quantity and diverse product ranges, but there are still several barriers to entry for prospective companies. Among them are material properties, surface finish, accuracy, build speed, high cost of equipment and maintenance.

Rapid manufacturing has so far been found to be most appropriate in industries where the component price is high and the production volume is low, but due to poor surface finish, application may be limited to parts being small and hidden from view, such as the wiring looms and engine parts pioneered by Client A and Client D's hearing aids.

Among the suppliers and consultancies interviewed it was evident that neither were solely dependant upon a single manufacturing process, ensuring maximum flexibility is maintained. Therefore it could be recommended that low-volume manufacturing could be first implemented, followed by Rapid Tooling (RT) and Rapid Manufacturing (RM) machines such as Selective Laser Sintering (SLS) & Direct Metal Laser Sintering (DMLS) as a supplement to the traditional manufacturing processes already present. A question prospective companies may have to ask themselves is whether the extra cost of a very small lot size is justified by faster response, extra product features or improved performance. A current half way house could be to subcontract relevant product lines in order to give companies a taste of the possibilities and performance benefits RM could offer to their business, thus avoiding the risks of full investment.

Aim 3 - To investigate the potential affects RM can have on the design process

It has been discovered that the implementation of RM can have a dramatic change on the traditional design process. The rapid manufacturing companies interviewed operated a heavily CAD orientated design process, which contrasted dramatically to the more traditional design process operated by Company D. It appeared that further design iterations were possible with RM in a much shorter timescale, and with CAD in place at an earlier stage it enabled the ability to virtually prototype and analyse the product to further increase performance. There were, however, some similarities and trends between the companies. Design for manufacture and assembly was still evident within the rapid manufacture design process, in the new form of "Design for

Rapid Manufacture" or "DFRM". Such elements involved the allowance for machine tolerances, surface finish, and other components - revealing that total geometric freedom is not always permitted due to other parts within the assembly, for example batteries and PCB's.

Aim 4 - To develop a RM design process model for prospective businesses

A design process model has been developed for prospective companies that reflect the current strategies carried out by the UK's leading rapid manufacturing suppliers. Company D has provided a hypothetical base for the analysis of the conversion from traditional manufacturing techniques to the implementation of rapid production. A distinct change in business structure would have to be undertaken by all stakeholders if Company D were to implement rapid manufacturing techniques.

Aim 5 - To discover the future potential for RM

There seems to be a clear lack of education and public awareness of the benefits rapid manufacturing can offer. With just a few dozen RM materials commercially available today spread out over all classes of materials such as plastics, metals and ceramics, perhaps a different approach to utilising resins could be investigated. Instead of trying to replace metal and plastics, new applications of resins could be found to ideally suit the characteristics and properties that photopolymers have to offer, spawning a new demand for the technology in diverse market places, such as the production of organs and human tissue pioneered by Academic A.

Word Count (Introduction to Conclusions)

8,580

8.0 References

Anon (2001), "The Solid Future of Rapid Prototyping", The Economist Technology Quarterly, 24 March, pp 47-9.

Dickens, Phil (2004) "Industrial Revolution Rapidly Approaching" Metalworking Production, 4th May

Dickens Phil, Campbell I, R Hague (2003) "Implications on Design of Rapid Manufacturing" IMechE Vol 217 Part C

Gibson, I (2006) "The Use of Rapid Prototyping to Assist Medical Applications" Vol 12 No 1, pp53-58

Green, S (2006) "Application of Rapid Manufacturing for the production of custom hearing instruments" www.siemens-hearing.com/ (3rd April 2007)

Grenda, E (2007) "Worldwide Guide to Rapid Prototyping" http://home.att.net/~castleisland/ (3rd March 2007)

Hague, R and Dickens, P.M (2003), "Design Opportunities with rapid manufacturing", Vol 23 No 4, pp346-356

Hague, R and Dickens, P (2007) "Solid Freeform Fabrication Proc.", pp11-13.

Hopkinson, N (2005) "Potential for Rapid Manufacturing by SLS to assist with design for the environment", Proceedings from the NASUG, SLSUG joint conference, Tuscan, Arizona

Kochan, A (2003) "Rapid Prototyping Helps Renault F1 Team UK Improve Championship Prospects" Vol 23 No4, pp 336-339

Mansour, S and R Hague (2003) "Impact of Rapid Manufacturing on Design for Manufacture for Injection Moulding", Vol 217, pp 453-461

Massimiliano, R and Hague, R (2007) "Make or Buy Analysis for Rapid Manufacturing" Vol 13 No 1, pp23-29

Maniscalco, Michelle (2003) "Choosing Resins in the 21st century". IMM Magazine, March 2003.

Rosen, David W (2004) "Overview of the WTEC Additive/Subtractive Manufacturing Study of European Research" Solid Freeform Fabrication Proc.pp1-10.

Ruffo, M (2006) "Cost estimation for Rapid Manufacturing - laser sintered production for low to medium volumes" IMechE Vol 220 Part B

Sachs, E (2001) "Manufacturing by Solid Freeform Fabrication" Solid Freeform Fabrication Proceedings, pp 596-618.

Time Compression Technologies Magazine (2000), "Rapid Manufacturing - Using additive manufacturing processes for production", Vol. 8 No.4, August, pp 53-58

Upcraft, S and Fletcher, R (2003) "The Rapid Manufacturing Technologies", Vol 23 No. 4, 2003 pp 318 - 330

Watkins, K.G. (2004) "Solid Freeform Fabrication and the Interface with Direct Solid Freeform Fabrication" Proc pp 14-25.